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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Small Fast Multi-Use Hydrogen Fuel Cell Harbor Craft Project

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

This document is the final report for the Small Fast Multi-Use Harbor Craft project PIR-20-003 conducted by Zero Emission Industries, Inc. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

In this project, Zero Emission Industries, Inc., designed, built, and demonstrated a hydrogen fuel cell harbor craft vessel. The project repowered a 27ft harbor craft vessel with a high-performance fuel cell power system, using compressed hydrogen as a fuel. Flexible gaseous hydrogen refueling solutions were developed to support the harbor craft demonstration in Northern and Southern California. Independent analysis of the vessel's demonstration data was conducted by the University of California, Irvine.

Overall, the demonstration project proved the feasibility of hydrogen fuel cell technology in marine applications, specifically harbor craft. The vessel delivered performance characteristics comparable to internal combustion engine-powered vessels while offering key advantages in efficiency, maneuverability, noise reduction, and safety. While minor refinements in handling and data interface usability could enhance operator experience, the results indicate that fuel cell-powered vessels present a promising alternative to conventional marine propulsion systems. These findings support California's clean energy and climate goals by validating a zero-emission pathway for commercial harbor craft.

Keywords: commercial harbor craft, hydrogen, fuel cell, mobile refueling

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Background

California is committed to reducing emissions to improve air quality, public health, and economic resilience. Maritime operations are essential to the state's economy but are also a major source of diesel particulate emissions. These emissions contribute significantly to air pollution and cancer risk, especially in low-income communities near ports. Replacing internal combustion engines in marine vessels with zero-emission alternatives supports the state's climate and clean air goals.

Hydrogen fuel cells, which have been used in other industries, offer a viable alternative with significant advantages over both batteries and diesel engines. However, their use in the U.S. maritime sector is still in its early stages, with only one commercial vessel in the U.S., the *Sea Change* ferry, that has demonstrated the technology.

The state has over 3,310 commercial harbor craft and approximately 600,000 active motorized recreational vessels. If these were converted to hydrogen fuel cells and fueled with zero carbon hydrogen, the greenhouse gas reductions could account for over 2.5 million metric tons of carbon dioxide equivalent emissions per year, or roughly 25 percent of emissions from the aviation, rail, and shipping sectors combined. The increased demand, up to 114,000 metric tons per year of hydrogen, assuming 100 percent transition from commercial and recreational crafts, would support the development of hydrogen infrastructure, reducing fuel costs across all sectors seeking to adopt hydrogen as a decarbonization solution, including on-road vehicles, other port equipment, and various fossil gas end-uses.

Project Purpose and Approach

The "Small Fast Multi-Use Harbor Craft Project" designed and built four key technologies to enable the broader feasibility of using hydrogen fuel cells in marine applications: Small Fast Harbor Craft, Mobile Refueling Truck, Fueling Interface Box, and Emergency Fuel Tank.

Small Fast Harbor Craft (SFHC)

The SFHC, named the FCV Vanguard, is a 27 ft power boat-style vessel that Zero Emission Industries (ZEI) converted to be powered by two 80 kilowatt (kW) fuel cells. The FCV Vanguard can store 9.8 kilogram (kg) of gaseous hydrogen onboard at 700 bar pressure. High-purity hydrogen stored in these tanks is delivered to the fuel cells, which generate electricity. A high voltage battery and power electronics system manage and deliver the produced electricity to an electric traction motor which serves as the main propulsion. The electric motor couples with a sterndrive which drives a propeller at the aft of the boat. ZEI designed the overall fuel cell powertrain, mechanical drivetrain, hydrogen fueling method, compressed hydrogen storage system, and fuel delivery system for the vessel.

The complete hydrogen system for the boat was constructed, assembled, tested, and commissioned at ZEI's facility. On water commissioning for the FCV Vanguard was conducted at Oyster Point, a local marina near San Francisco.

Mobile Refueling Truck (MRT)

The MRT is a mobile hydrogen fuel source for the SFHC. Marine-serving hydrogen fueling stations are not currently available, so ZEI designed and constructed the MRT to transport fuel to any location where the SFHC is operated.

ZEI procured a truck to serve as the platform for the MRT. It required suitable load capacity to support two commercial off-the-shelf U.S. Department of Transportation-approved compressed hydrogen tank systems. Together, the total hydrogen storage capacity is close to 40 kg at 700 bar. The system is mounted using standard shipping container corner mounts. ZEI modified the tank packages to enable the MRT to deliver hydrogen fuel to the SFHC using a common hydrogen fueling interface.

The MRT was constructed at ZEI's facility. Commissioning of the system followed manufacturer recommendations for purging and initial pressurization. ZEI refueled the MRT at public hydrogen fuel stations in coordination with the station operators during off-peak hours to not disrupt on-road vehicle fueling needs.

Fueling Interface Box (FIB)

The FIB functions as a mobile hydrogen dispenser designed for easy use with minimal training. The FIB is the size of a large suitcase and contains automated components to make a simple hydrogen flow controller that transfers gaseous hydrogen efficiently and safely in the field. The FIB can be used beyond marine applications, encompassing any gaseous hydrogen fueling operation that is programmed into its control software.

Emergency Fuel Tank (EFT)

The EFT provides additional fuel in the event that the SFHC runs out of hydrogen in an inopportune location where refueling is not possible. The EFT is a simple system that includes a hydrogen storage tank and valving.

Key Results

The demonstration covered 24 events - 13 in San Francisco Bay and 11 near the San Pedro ports. Over this period, the vessel operated for more than 80 hours, traveling 217 nautical miles while consuming 63.4 kg of hydrogen.

Energy analysis revealed that 35 percent of the hydrogen input was converted into propulsion power, with the most significant energy losses occurring during the conversion from hydrogen to electricity. The vessel's overall efficiency remained above 34 percent when power demand exceeded 80 kW. The propulsion motor's efficiency improved with speed, regularly exceeding

90 percent at speeds above 2,000 RPM. The estimated fuel economy of the Vanguard operating at 25 knots is 6.28 nautical miles per gallon gasoline equivalent. Fuel consumption for boats of similar size and engine power yield an average fuel economy at 25 knots of 3.64 nautical miles per diesel gallon, highlighting the significant improvement of fuel efficiency when compared to traditional fossil fuels.

Data was captured on SFHC fills from the MRT, regulated by the FIB. On average, 4.62 kg of fuel was transferred in about 11 minutes and 23 seconds. The largest and smallest fills were 7.67 kg, taking 28 minutes and 59 seconds and 3 kg, taking 5 minutes and 18 seconds respectively. The highest recorded fill temperature was 82°C, just below the 85°C limit set by the tank original equipment manufacturers (OEM).

Operator feedback was largely positive. Operators noted that the electric drive system enabled smoother speed adjustments and enhanced docking control due to instant torque application. Additionally, the significantly quieter operation reduced operator fatigue and created a more comfortable experience.

A total cost of ownership (TCO) analysis was conducted to evaluate the economic feasibility of hydrogen fuel cell vessels like the FCV Vanguard. The analysis incorporated cost projections for fuel cell systems, hydrogen storage, and battery components and compared them to the TCO of a diesel internal combustion engine. The analysis found that fuel is by far the most significant factor in determining TCO of commercial harbor crafts. The analysis concluded that TCO of hydrogen fuel cell harbor crafts today underperform diesel equivalents. Given projected reductions in fuel and technology costs, the analysis found that the TCO of hydrogen fuel cell harbor crafts would fall under the TCO of diesel equivalents by 2035.

Overall, the demonstration project proved the feasibility of hydrogen fuel cell technology in marine applications, specifically harbor craft. The vessel delivered performance characteristics comparable to internal combustion engine-powered boats while offering key advantages in efficiency, maneuverability, noise reduction, and safety.

Knowledge Transfer and Next Steps

ZEI conducted technology transfer activities through extensive stakeholder engagement, media outreach, and public demonstrations. Additionally, ZEI issued two major press releases and collaborated with journalists to publish articles and participate in industry podcasts, further raising awareness of hydrogen as a zero-emission maritime solution.

Beyond media efforts, ZEI engaged directly with key regulatory bodies, industry stakeholders, and the public. The team presented to the U.S. Coast Guard on hydrogen safety and marine regulations, hosted site visits for agencies like the U.S. Department of Energy and organized a public launch event as part of SF TechWeek, which attracted over 150 attendees. ZEI also conducted hands-on demonstrations in Southern California, offering ride-alongs to public agencies, port operators, and environmental planners.

The project validated the technical and market potential for these solutions but require additional testing and optimization to be fully actualized as commercial products. In addition, market forces such as hydrogen price and fuel availability must improve to validate fuel cells from an economic perspective. Finally, hydrogen specific codes and standards must be developed so this technology can be deployed for commercial purposes in regulatorily predictable and satisfactory ways.

CHAPTER 1: Introduction

California has set emission goals which seek to improve air quality and support the health and economic resiliency of its residents. Maritime operations around ports and inland waterways play a critical role in the state's economy but are major emitters of diesel particulate matters which increase near-source cancer risk in surrounding communities, many of which are low-income and disadvantaged.

Replacing the current technology used for powered marine vessels, internal combustion engines (ICE), is one strategy to reduce emissions. Batteries have been demonstrated to serve some small, low-speed vessels as a zero-emission alternative, but greater adoption is hindered by performance limitations. Hydrogen fuel cells pose unique value to operators beyond that of batteries and ICEs, yet fuel cells have only been demonstrated in a single U.S. commercial maritime use case.[1]

Table 1 compares the benefits of hydrogen fuel cells with other competing technologies.

Table 1: Maritime Powertrain Competition Matrix

Comparable Attribute	Hydrogen fuel cells	Diesel and gasoline ICEs	Battery electric
Lower total cost of ownership	+	o	+
Feasibility for a wide range of vessel types and uses	+	++	--
Maintenance cost and downtime	+	--	++
Modularity and flexibility of arrangement	++	-	++
Sales/marketing benefit	++	--	++
Low noise	++	-	++
Vessel speed and power	+	++	o
Vessel endurance	+	++	--
Energy efficiency	+	-	++
Provides health benefits for crew or passengers	++	--	++
Operations flexibility	+	++	--
Capable of producing drinking water onboard	+	--	--
Fuel/energy future price stability	+	--	+
Zero emissions onboard	++	--	++
Zero emissions "well-to-waves" potential	+	--	+
System volume	-	++	--
System weight	o	+	--

1 See : https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration-project

Source: Zero Emission Industries "+" is more favorable, "-" is less favorable, and "o" is neutral

Hydrogen fuel cells have been used for decades in a variety of stationary power, material handling, and mobility applications. There are two major aspects of hydrogen fuel cell use in any application: (1) the cost and performance of the fuel cell power generator and (2) the availability and cost of hydrogen fuel in the form needed by the fuel cell system.

The light-duty vehicle market is a case where the technology is capable of meeting or exceeding the performance of current combustion-engine vehicles, as proven by current fuel cell electric vehicles (FCEV) from Toyota, Hyundai, and Honda. The potential adoption of FCEVs is in the millions and at that production volume would have a very large impact on reducing the cost of the fuel cell technology for all applications.[2] The resulting multiplicative impact of low-cost fuel cells producing zero emission power in a range of use cases would reduce harmful emissions from the transportation sector. However, the availability and cost of hydrogen fuel for FCEVs is impeding their adoption. This is largely because of the high cost and long development times of the retail hydrogen fueling stations combined with the low consumption of hydrogen on a per-vehicle basis.

In comparison, the marine application consumes vastly higher quantities of hydrogen on a daily basis: a single, typical harbor craft can consume as much hydrogen as 2,000 light-duty vehicles. This large consumption volume and consistent, high-hour usage of marine vessels results in lower-cost hydrogen fuel and a better economic use case. Conversations with industrial hydrogen suppliers described in a relevant study estimate hydrogen costs in the $5-$6 range for a single passenger ferry consuming 2,000 kg per day[3], which is about 3-6 times less than the current retail price of hydrogen at FCEV fueling stations. Furthermore, consumption of just a few large cargo ships – which can consume 10's of tons per day – is sufficient to justify the construction of new hydrogen production facilities. Just as the FCEV market can work to reduce the cost of fuel cells, the marine market can reduce the cost of hydrogen. In fact, the two markets can work together for the success of both.

Unfortunately, the marine application of fuel cells lags significantly behind that of on-road FCEVs. This is due to a combination of factors: misunderstanding and under-appreciation of the market, absence of a regulatory framework at the US Coast Guard, and technical differences between on-road light duty fuel cells and those needed for use in the marine environment. The lack of proven marine-specific hydrogen fuel cell technology solutions – evidenced by deployments – greatly impedes adoption of the technology in this application.

As mentioned above, only a single commercial fuel cell vessel has been developed in the U.S., the Sea Change ferry. This vessel proves that medium-sized passenger vessels can be

[2] S. Satyapal, "Hydrogen & Fuel Cells—Program Overview," US Department of Energy Hydrogen and Fuel Cells Program 2013 Annual Merit Review, Arlington, VA.

[3] J. Pratt and L. Klebanoff, "Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry," Sandia Report SAND2016-9719, available from: maritime.sandia.gov

powered by hydrogen fuel cell technology. However, marine industry adopters do not usually accept a new solution until it is proven in their particular segment, even if the underlying technology is the same.

This project validates the small fast harbor craft vessel segment. A zero-emission solution for small fast harbor craft vessels can have a profound impact on the market, the economy, and air quality. California alone is home to over one million vessels, over 98 percent of which are under 40 feet long and have a wide variety of uses: patrol, fire/rescue, fishing, pilot, excursion, ferry/taxi, and recreation with speeds from a few knots to over 50 knots.

The low-cost, zero emission powertrain developed and demonstrated through this effort can enable hundreds of harbor craft and hundreds of thousands of other small vessels in the state to use zero emission hydrogen fuel cells. This directly eliminates diesel and gasoline consumption, and emissions of air pollutants and greenhouse gases (GHG) from these vessels. With long term goals of decreasing costs of hydrogen fuel and fuel cell technology in combination with increasing diesel prices, it will also result in lower costs for the owners and operators of the vessels, and ultimately for passengers who ride on them. Finally, the increase in hydrogen consumption statewide provides an attractive business case to further build out the supporting renewable hydrogen production, distribution, and fueling network that can be leveraged by all other fuel cell applications creating an exponential-growth scenario of hydrogen fuel cell adoption.

To help illustrate this impact, an analysis of vessel emission avoidance was conducted. Per-vessel avoided fuel and emissions were calculated by characterizing existing vessel powertrains in terms of installed power, load factor, annual operating hours, emission factors (for criteria pollutants), and fuel carbon intensity (for GHGs). The method and input parameters are as specified by the California Air Resource Board (CARB) Carl Moyer program.[4] The calculation input assumptions are shown below, with parameters from the Carl Moyer method designated with (CM)[5]:

- Average installed power: 333 hp (250 kW)
- Average load factor (CM)6: 0.44
- Fuel consumption rate factor (CM): 18.5 bhp-hr/gal
- Energy Economy Ratio (CM): 1.9

[4] See: https://ww2.arb.ca.gov/guidelines-carl-moyer

[5] For purposes of these calculations, emission factors for diesel were used for gasoline as well. This is conservative because gasoline emission factors are shown to be higher than those of diesel (ref. 12)

[6] Assuming an equal mix of charter fishing (0.52), ferry/excursion (0.42), and crew/supply (0.38) (taken also as representative of a patrol boat)

- Average annual operating hours, commercial7: 2,500
- Average annual operating hours, recreational8: 98
- Diesel emission factors (CM): 3.87 gNOx/bhp-hr, 0.49 gROG/bhp-hr, 0.068 gPM10/bhp-hr, combined to a Weighted Emissions Reductions (WER) factor per the Carl Moyer method: WER = NOx + ROG + 20*PM10.
- Diesel carbon intensity (CM): 134.47 gCO2e/MJ

Single commercial harbor craft vessel results:

- Avoided diesel fuel: 19,818 gal/year
- Avoided criteria pollutants (WER): 2.31 ton/year
- Avoided GHG: 272 MT/year
- Hydrogen consumption: 11.7 MT/year

Single recreational vessel results:

- Avoided gasoline fuel: 777 gal/year
- Avoided criteria pollutants (WER): 0.01 ton/year
- Avoided GHG: 11 MT/year
- Hydrogen consumption: 458 kg/year

Assuming a fleet-average vessel, the per-vessel results can be multiplied by the number of vessels in the fleet that are assumed to be made zero emission, which can be done in a time-dependent method. CARB's 2020 Commercial Harbor Craft survey[9] lists a total of 3,310 commercial harbor craft in the state with 417 excursion, 508 commercial passenger fishing, and 167 crew/supply (taken also as representative of patrol boats). It is assumed that 35 percent of these types of commercial vessels (total 382) are of similar power to this work and can be readily constructed or adapted to the fuel cell powerplant developed here with similar emission benefits. For recreational vessels, California vessel registrations[10] (non-USCG certificated vessels) show approximately 600,000 active motorized vessels in the state. A

[7] Representative of typical excursion vessel hours from stakeholder Red and White Fleet and also used as representative for charter fishing hours. Heavy use ferry can be more than 5,000 hr/y so this is conservative.

[8] USCG Recreational Boating Survey: https://uscgboating.org/library/recreational-boating-servey/USCG-2011-NRBS-Report.pdf

[9] See: https://ww2.arb.ca.gov/sites/default/files/2020-09/CHC%20Workshop%20September%202020.pdf

[10] See: https://dbw.parks.ca.gov/pages/28702/files/December%202018%20-%20Total%20Vessel%20Registration%20by%20County.pdf

USCG recreational boat engine-size survey[11] shows approximately 75 percent of them are much smaller than the 250 kW engine in this work, so a correction factor of 0.40 (calculated from the engine size distribution) is used to reduce the impact on fuel consumption and emissions to a more realistic value. Table 2 summarizes the total potential impact for a notional 20-year transition timeline consistent with other State initiatives to eliminate transportation-source emissions on land and in marine. Because this is zero emission technology, the "business as usual" case is one that does not realize any of these fuel or emission reductions, nor the increased hydrogen consumption.

Table 2: California Benefits: Avoided Fuel and Emissions and Added Hydrogen Demand Based on the Conversion of the Small Vessels to Zero Emission Hydrogen Fuel Cells Made Possible by the Results of this Project.

		Avoided fuel (million gal/yr)		H2 Demand (thous. MT/yr)		Avoided WER (thous. ton/yr)		Avoided GHG (thous. MT/yr)	
Year	**Adoption Rate**	**Comm. (diesel)**	**Rec. (gas)**	**Comm.**	**Rec.**	**Comm.**	**Rec.**	**Comm.**	**Rec.**
2026	10%	0.8	19	0.45	11	0.09	2.2	10	256
2028	20%	1.5	37	0.89	22	0.18	4.3	21	512
2030	30%	2.3	56	1.3	33	0.26	6.5	31	767
2032	40%	3.0	75	1.8	44	0.35	8.7	42	1,023
2034	50%	3.8	93	2.2	55	0.44	11	52	1,279
2036	60%	4.5	112	2.7	66	0.53	13	62	1,535
2038	70%	5.3	131	3.1	77	0.62	15	73	1,790
2040	80%	6.1	149	3.6	88	0.71	17	83	2,046
2042	90%	6.8	168	4.0	99	0.79	20	93	2,302
2044	100%	7.6	186	4.5	110	0.88	22	104	2,558
TOTAL @ 100%		194,000,000 gal/yr		114,000 MT/yr		23,000 ton/yr		2,661,000 MT/yr	

Source: Zero Emission Industries

The emissions savings are significant for Californians. The potential GHG emissions savings alone is about 25 percent of the total GHG emission from the "Aviation + Rail + Ships" category in the 2017 GHG inventory.[12] The potential annual hydrogen consumption is equivalent to that of nearly 500,000 light duty FCEVs and would work to significantly increase hydrogen demand and could lead to decreased hydrogen costs across all sectors.

To help enable the transition of future hydrogen vessel adoption and avoid the pitfalls of the light duty market, the project additionally set out to develop and build technologies that would support a hydrogen fueling ecosystem. The vessel can be fueled through the project-

[11] USCG Recreational Boating Survey: https://uscgboating.org/library/recreational-boating-servey/USCG-2011-NRBS-Report.pdf

[12] See: https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2017/ghg_inventory_trends_00-17.pdf

developed novel mobile truck-mounted storage system, which can be refueled at California's retail hydrogen fueling stations; a portable fuel transfer box able to bring the fuel over long distances and overwater to fuel the boat from the truck; and an additional low storage portable tank for use in emergency scenarios. The key attribute of this system is it is highly flexible and functional in a wide range of use cases and environments, and because no shoreside infrastructure is required, it is extremely cost effective and immediately deployable at any site.

CHAPTER 2: Project Approach

The completion of the Small Fast Multi-Use Harbor Craft project was conducted over four primary phases: design, build, commissioning, and demonstration. The design, build, and commissioning stages were completed individually for the SFHC as well as each refueling system with the demonstration phase utilizing all equipment as a collective mobile hydrogen infrastructure and offtake ecosystem. Below is a review of the approach taken in these phases.

Small Fast Harbor Craft (SFHC)

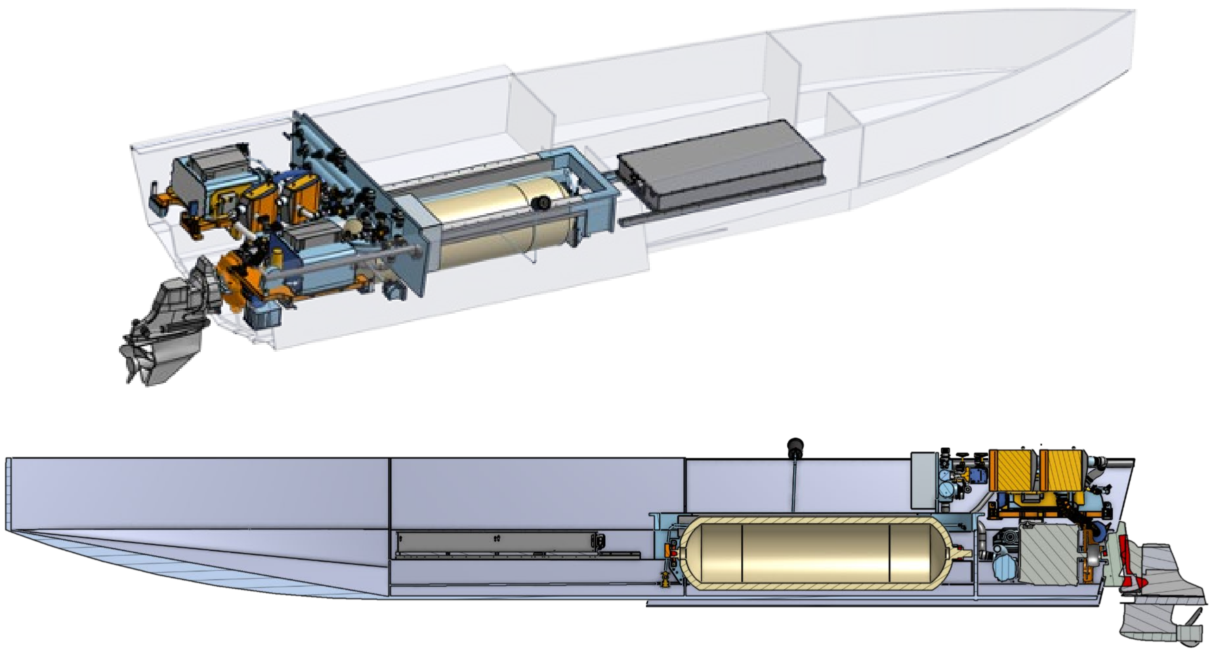
Zero Emission Industries, Inc., (ZEI) repowered a 1995 27ft powerboat with a first of its kind hydrogen powertrain package. The boat was built for high performance, housing its original internal combustion engine and fuel storage within a tight hull form factor meant to endure extreme shock and vibrations while under high speeds, delivering ZEI a platform for testing the limits of fuel cell power on the water in typical commercial harbor craft use cases.

Powertrain Package Design

The SFHC fuel cell powertrain package includes: (1) fuel cells; (2) compressed hydrogen storage system (high pressure tank); (3) high voltage battery; (4) cooling system; (5) power electronics and controls; and (6) electric drivetrain.

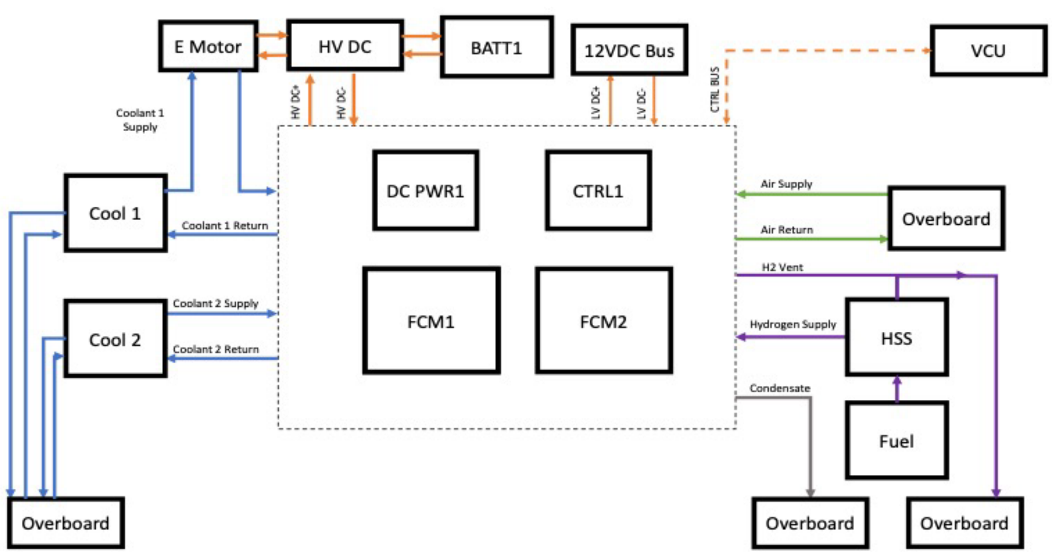
Figure 1 is a rendering of the small fast harbor craft with primary subsystems arranged in the hull. The gray rectangular prism toward the bow of the boat represents the system's high voltage battery. The cylindrical component aft of the battery is the compressed hydrogen storage tank. The fuel cells, electric motor, and many of the system's balance of plant components are located in the aft section of the boat where the original ICE was housed. Figure 2 depicts a high level line diagram of the vessel's primary sub-systems.

Figure 1: 3D Vessel Component Arrangement Renderings



Source: Zero Emission Industries

Figure 2: Line Diagram of Primary Vessel Sub-Systems



Source: Zero Emission Industries

Fuel Cells

Similar to ICE systems found throughout maritime, the only inputs required for the fuel cells to operate are ambient air, fuel, and thermal management fluids in the form of sea water.

The fuel cells are the sole source of electricity generation on the SFHC. Fuel cells produce unidirectional direct current (DC) power by reacting hydrogen and the oxygen in air on a catalyst. It is not a combustion process, and the only byproduct is water, thus they are considered zero emissions. The SFHC includes two fuel cell modules each rated to 80kW, for a total of 160kW of nominal net power (90 kW, and 180 kW gross power respectively - net power takes into account the power losses that it takes to run all of the balance of plant components to make the fuel cell function).

The SFHC employs fuel cells designed for the light duty automotive market and adapted them to marine environments. Automotive fuel cells were leveraged for their high power to weight ratio as well as drastically lower lead times. Cost was also a factor in the selection of automotive fuel cells, with automotive options coming in lower than their alternatives.

ZEI kept the core fuel cell modules largely unchanged as delivered from the supplier, however they optimized the fuel cell package to operate in a marine environment under expected load conditions found therein. The system was designed with a novel set of balance of plant componentry primarily modifying the cooling system which enables the project team to reliably push the fuel cells beyond their rated power limits. Additionally, the system structure was modified to be able to withstand the shock and vibrations of continuous high-power operation on the water.

ZEI initially commissioned the hydrogen fuel cell power system on a test bed (Figure 3) rather than the boat. This allowed the project team to continue simultaneously developing the boat hull, while methodically testing each fuel cell system component in a controlled and repeatable environment.

Figure 3: Fuel Cell Test Stand Hydrogen Delivery System and Commissioning Exhaust

Source: Zero Emission Industries

The primary differences between the test bench and the final product are the cooling system and the hydrogen supply system. Once the initial system was commissioned, the team mated final cooling and hydrogen supply subsystems with the powertrain during installation in the boat for the build phase.

Compressed Hydrogen Storage System (CHSS)

Hydrogen was stored on the SFHC using a 10 kg type 4 tank mounted forward of the engine compartment. The compressed tank can be filled through a fueling port located on the port exterior of the vessel. The CHSS can be fueled at retail fueling station by mating with a common SAE J2600 connector found therein. In addition, any gaseous hydrogen source can fuel the CHSS through the use of the SFHC project's FIB.

The entire CHSS is inside a container inside the hull to maximize space on the boat, protect the hydrogen components, and isolate a potential hydrogen leak from the CHSS. The tank is mounted to structural components attached to the hull of the boat that were designed and fabricated by ZEI. Boats experience higher g-forces and vibrations than on road cars due to a lack of suspension and rough water conditions. ZEI engineers worked extensively to develop a robust mounting system for the tank and associated components.

The hydrogen storage system for this boat underwent a rigorous hazard identification and risk analysis process which governed the design of the system. The hydrogen tank includes an integrated valve from the factory, minimizing leak points. The containment area within the SFHC has a combustible gas detector which in the presence of any detectable amount of hydrogen automatically activate safety procedures. Ventilation fans continuously exhaust the enclosed area safely overboard to limit the development of a flammable atmosphere resulting from abnormal leaks. Additional safety measures take the form of a temperature pressure relief device valve already built into the tank which at the presence of an open flame will vent the hydrogen out of the boat through a dedicated vent line.

High Voltage Battery

A marinized high voltage battery provides power when the fuel cell is ramping up and helps keep the fuel cell operating at the most efficient power point. Most automotive applications run at 400V, yet the fuel cell modules can output over 600V. In practice, two typical automotive batteries could be connected, but having two batteries did not meet the space and weight requirements of the SFHC. ZEI did extensive market research to locate a supplier and worked with them to procure and integrate batteries into the ZEI powertrain. To add an additional layer of power system redundancy during system testing, ZEI decided to install a larger battery than is necessary and developed a battery only drive mode which could help limp the boat to safety in the event of fuel cell system failure. The battery module installed has a capacity of 23 kWh.

While there were no major changes to the battery itself, ZEI engineers invested significant time into coupling the battery to the fuel cell modules electrically and designing the logic for the two modules to interact. The physical coupling was achieved through the selection of the correct DC-DC converter which boosts the power from the fuel cells to the correct voltage held by the battery. The digital coupling was achieved through the development of software which makes certain that the battery assists the fuel cells in the ramping up of power to not damage the fuel cells as well as providing an outlet to accept power during the ramping down of the fuel cells.

Cooling System

ZEI developed a custom balance of plant cooling system for the SFHC's power package. It is responsible for keeping the temperatures within specification for all major power components on the boat including the fuel cells, power electronics, motor, and battery, each with different pressure, flow and heat dissipation requirements. All components are cooled with engineered cooling fluids that run through heat exchangers. The other side of the heat exchangers are fed by a pump that intakes water from the body of water on which the boat sits. Whereas automotive fuel cell systems use air/liquid radiators and fans, the SFHC uses a liquid/liquid heat exchanger. The liquid/liquid cooling system enables improved cooling system performance through the greater heat transfer capacity of liquid over air.

The ZEI team divided the components into multiple cooling loops. The most challenging loop was the stack coolant due to material compatibility issues. ZEI designed and worked with a partner to manufacture heat exchangers for the fuel cell stack cooling. The tubing material to duct the coolant also had to be specially sourced by ZEI to support the material compatibility, flow, and pressure requirements.

The original coolant pumps on the boat were driven by a belt drive system coupled to the engine. ZEI elected to replace this system with electric pumps. This offered more control and was better integrated with the overall electric architecture of the boat. ZEI's system controller monitors these temperatures and can actively adjust the coolant system to meet the system requirements.

Power Electronics and Controls

The ZEI powertrain output is electricity; thus, ZEI made an effort to electrify all components on the SFHC. The electrical system on the SFHC has both alternating current (AC) and DC components. The primary functions are to spin the electric motor and support boat systems. While some components come with simple plugs and connectors, others had to be custom made to integrate with the overall powertrain system. High voltage components, up to 800V, require special care for safety and noise immunity.

The high voltage DC system was a strong focus for ZEI engineers. The high voltage DC system is composed of the fuel cell system, high voltage battery, junction box, motor, motor inverter and power converter. Much of the focus was on the high voltage DC junction box. This is the singular point in the electrical system where all the DC power flow from the fuel cells, battery and motor come together.

All of the high voltage componentry electrically upstream from the electric motor utilizes a DC current whereas the electric motor utilizes AC power. To convert the power being supplied to the motor from the fuel cells and the battery from DC to AC, an inverter is used. ZEI sourced an electric motor that included its own inverter.

ZEI installed a 12V battery for energy storage on the low voltage DC system but had to engineer a solution to rapidly charge this battery from the high voltage bus due to the high auxiliary load composed of pumps, fans, screens, sensors, and controllers. Additionally, ZEI had to design and build a load center for distributing the 12V and protecting each circuit.

To manage all the separate components that comprise the SFHC power package, ZEI designed an Electronic Control Unit (ECU) and its underlying software. The development of this software required the connection of disparate technologies and components not originally designed to work together as a packaged power system.

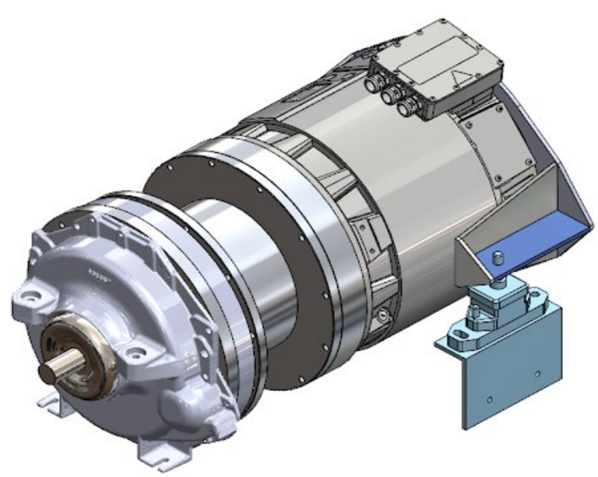
Safety was a primary concern throughout the controls design of the SFHC. Numerous safety interlocks are programmed into the controls to mitigate risks regarding hydrogen safety, power system longevity, and vessel operation. ZEI's engineers have undertaken significant tasking to build a standalone system that when active allows a user to operate the SFHC much as they would a conventional vessel with little training on the power systems.

Electric Driveline

The drivetrain was one of the most challenging efforts undertaken by the ZEI team. The SFHC has a sterndrive system that is mounted to the hull of the boat in a fixed location. Sourcing an electric motor that properly drives the sterndrive and propeller was challenging. Electric motors are often rated for automotive environments where duty cycles are short. Boats require full power output for long durations. Motors need to be robust enough to account for this operating profile. Additionally, the marine environment introduces challenges such as salty air and water splash that are not encountered in the automotive world. ZEI engineers were able to source a motor that met the specifications for the SFHC for weight, space and performance.

Coupling the electric motor to the sterndrive was an additional challenge. The sterndrive shaft was coupled with the internal combustion engine shaft via a flex plate (Figure 4). The electric motor had tighter tolerances for shaft alignment than the internal combustion engine. To meet these requirements, ZEI had to design and fabricate the motor mount and coupling pieces with high precision. The electric motor mounting point is on the shaft face, which was different to the internal combustion engine mounted by right angle feet. ZEI designed custom brackets to connect the motor to the hull of the boat.

Figure 4: Driveline Assembly Rendering



Source: Zero Emission Industries

Vessel Hull Design

With the powertrain subsystems primarily designed, the ZEI team generated component arrangements within the hull of the SFHC as well as planned the necessary modifications for install of the new powertrain system.

To determine placement of significant weight components, ZEI engineers strongly considered center of gravity for the SFHC. The project team aimed to balance the port to starboard and bow to stern weight ratios while keeping vessel weight low in the hull to maximize performance, efficiency, and safety.

A balanced port and starboard weight is a crucial factor in achieving optimal vessel performance and safety. For this reason, many duplicative or similar weight profile components are mirrored along the length of the boat. More unique in shape and weight, components like the hydrogen storage tank and battery had to be placed along the boat's centerline.

Achieving a balanced bow to stern weight ratio is a critical factor in the vessel's ability to get on plane. Getting on plane refers to a vessel transitioning from traveling nose up through the water, requiring the drivetrain to overcome the thousands of gallons of water being displaced by the hull, to being propelled on the water's surface, reducing water displacement significantly. If weight is disproportionately located in the aft of the boat, a higher minimum speed is required to get on plane. Having the small fast harbor craft get on plane at a lower speed will reduce the power required from the drivetrain, in turn reducing fuel consumption while traversing the water.

ZEI designed modifications to the hull of the boat for installation of the fuel cell power package and hydrogen storage system. This included a cavity for the ventilated hydrogen enclosure space as well as a vertical structure that provided a mounting surface for the new electric drive components and served as the front wall of the engine enclosure.

SFHC Hull Prep and CHSS Install

To prepare for installation of the fuel cell power package, the ZEI team had to complete the previously described hull modifications. Before modification could begin, the project team stripped the boat of its previous ICE components and all material from the interior lining of the hull including seating, lighting, stereo equipment, floor and wall carpeting, and any glues or adhesives.

An oval was cut in the floor as well in the aft wall of the cabin to provide the necessary space for the installation of the CHSS vessel and its enclosure. Figure 5 depicts the intensive flap disc process that is necessary to prep the vessel's interior surface for fiberglass modification. In addition, the ZEI team constructed and installed a vertical surface made of Coosa Board into the aft of the boat.

Figure 5: Hull Prep

Source: Zero Emission Industries

All system components fixed to the hull are on ZEI designed and fabricated mounting structures (Figure 6). The build required installation of mounting points and reinforcing the boat hull in certain places to handle up to 20G loads and vibrations that might be experienced during operation. These structures utilize materials such as tube frames, fiber glassed plywood, 3-d printed composites, Coosa board, welded aluminum mounts, and more. To understand the robustness of the custom components ZEI performed finite element analysis on major components and where this did not occur, used generally conservative construction practices.

Figure 6: Aft Coosa Board Surface and Fuel Cell Mounts

Source: Zero Emission Industries

Power Package Build/Install

With the vessel hull appropriately prepped and the CHSS successfully installed, the project team installed the fuel cell power package (Figure7). The installation entails multiple weeks of dedicated efforts on an extensive list of tasks. A high level list of installation procedures can be found below:

- Fasten and align electric motor to boat hull and sterndrive
- Mount coolant pumps and filters to engine bay and vessel hull
- Mount heat exchangers to aft bulkhead
- Mate fuel cell space frame with hull fastened fuel cell vibration mounts
- Mount fuel cell heat exchangers to fuel cell space frame
- Fasten high voltage battery to hull stringer mounts
- Mount electrical handling components to aft bulkhead and vessel hull
- Mount ECU panel in vessel cabin
- Route electrical cabling between system components.
- Wire CAN network through vessel system components.
- Route cooling tubing between heat exchangers, pumps, and coolant recipients.
- Plumb hydrogen tubing
- Plumb system exhaust

Figure 7: Vessel Electric Motor and Drive Train Coupling

Source: Zero Emission Industries

Power Package CHSS Commissioning

Commissioning of the CHSS system included purging with inert gas, a leak check up to full pressure, and system purification.

ZEI purged the system using nitrogen first, which serves two purposes. First, to eliminate oxygen from the system prior to introducing hydrogen and second to perform an initial leak check with non-flammable gas. It has been ZEI's experience that a majority of leaks in hydrogen piping systems are found below 500 psi and thus leak check with nitrogen is an excellent first step. Once leaks were resolved, ZEI engineers purged the system with nitrogen repeatedly and vented the system pressure down to near atmospheric pressure.

Introducing hydrogen into a newly constructed system is a hazardous task that ZEI planned extensively for. All potential ignition sources are removed from the area and access is limited to necessary personnel. Additionally, ZEI uses handheld gas detectors to pinpoint the location of leaks. With these risk limiting practices in place, ZEI engineers began filling the CHSS via the fueling port. This pressurized the tank and high-pressure piping system. ZEI engineers pressurized the rest of the system slowly, checking for leaks at increasing pressure increments. Once the purification pressure was reached, ZEI bled the system back down and repeated the process until the fuel cell system hydrogen purity was achieved.

Full system pressurization with hydrogen is the riskiest step in CHSS commissioning. ZEI pressurized the CHSS using the MRT, which allowed ZEI to carefully control the flow of gas up to the maximum allowable working pressure of the CHSS.

Power Package Commissioning

Commissioning of the SFHC power package was conducted by ZEI in a staged approach to sequentially validate the system in increasingly entropic scenarios. The three stages of commissioning included: 1. Shop Trials; 2. Dock Trials; 3. Sea Trials.

Shop Trials

The purpose of the shop trial (Figure 8) was to emulate the load of the SFHC's main propulsion inverter and motor on the vessel's hydrogen fuel cell power system to validate system performance in a controlled environment. Out of water testing at the shop allowed the project team to isolate and remove many uncontrollable variables and safety concerns usually present on the water.

The shop trial was conducted in multiple phases to verify system performance at different system loads. Phases were designed to bring the system up from the previous phase's power state to a stable load profile according to the load schedule then to the initial state of the subsequent evolution. The completion of the shop trial marked the first successful operation of both fuel cell modules at continuous high power.

Figure 8: Shop Trials

Source: Zero Emission Industries

Dock Trials

The purpose of the dock trial (Figure 9) is to continuously operate the SFHC in a relatively controlled environment to validate low continuous load to the electric motor and sterndrive while testing the SFHCs basic seaworthiness. The ZEI team trailered the SFHC to a local marina and tied up the boat to concrete pillars, allowing the vessel to generate forward propulsion while maintaining its position. This controlled environment afforded the project team the ability to closely monitor critical components, which would otherwise be difficult to access while under full operation. Seaworthiness was validated by ensuring all typical vessel safety components such as bilge pumps, power steering, and trim operate as expected and no leaks or structural concerns were present.

Figure 9: Dock Trials

Source: Zero Emission Industries

Sea Trials

The purpose of the sea trials (Figure 10) was to operate the SFHC in open water, testing its powertrain system in various operational loads while validating its seaworthiness and data capture capabilities. Being the first time the SFHC would operate on open water, the project team put into place safety measures including a chase boat, safety procedures, a limited operating envelope, and a test area boundary. The sea trial was conducted in seven phases. Each phase included a break to capture manual data as well as to check vessel systems for damage from vibration and shock while under way.

Figure 10: Sea Trials

Source: Zero Emission Industries

Mobile Refueling Solutions

Access to hydrogen refueling infrastructure remains a barrier preventing greater adoption of fuel cell technology in both emerging and existing markets. Light duty stations provide fueling to on-road consumers located within a serviceable area but even with the growing station network, off-road applications and geographic markets that cannot economically justify the investment in permanent infrastructure require a solution. ZEI developed a mobile gaseous hydrogen fuel transfer ecosystem which facilitates the safe transportation and dispensing of hydrogen to solve this very challenge. The FIB, MRT, and EFT enable the project team to standup a temporary fuel station wherever one can drive a truck and successfully fuel the SFHC, or any gaseous hydrogen application.

Fuel Interface Box (FIB)

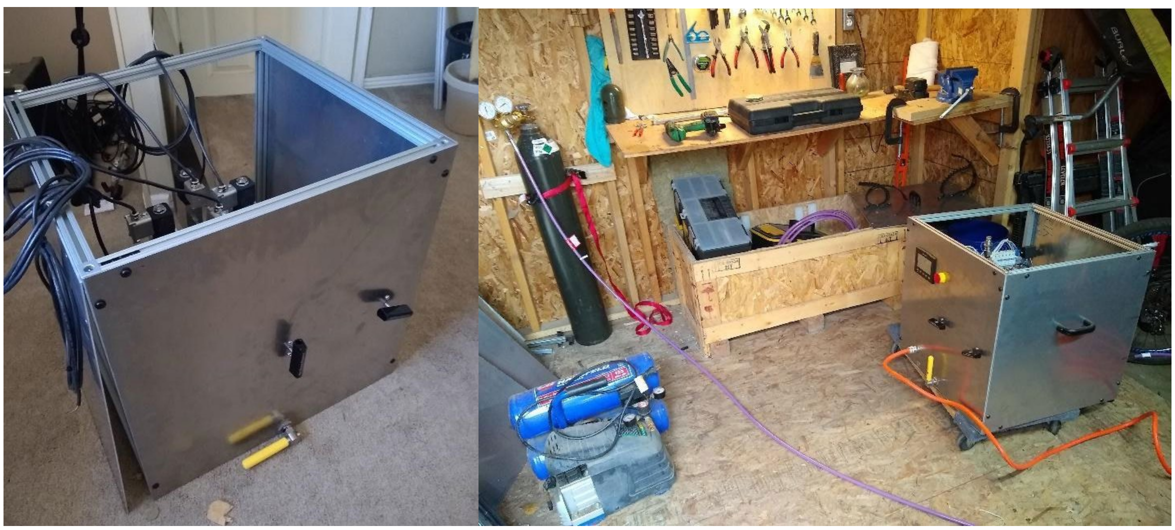
The FIB serves as a mechanism for safely transferring hydrogen from any gaseous hydrogen source under 1,000 bar to any hydrogen end-user; one example is between a tube trailer and the Small Fast Hydrogen Fuel Cell Harbor Craft. Designed alongside the SFHC and the MRT, the FIB creates a complete hydrogen ecosystem from upstream source to the assets in use. The FIB is designed to support hydrogen product expansion for simplified adoption across multiple industries. The novel ZEI design, process and procedure developed for the FIB unlocks safe and cost-reduced hydrogen fueling allowing for non-hydrogen experts to operate equipment and eliminates the need for prohibitively expensive stationary infrastructure. Equipped with industry standard nozzles and quick connects, the FIB can be modified to accommodate the connection points necessary for any fill scenario.

Operated through a touch screen, the FIB provides operators with simple to follow instructions to successfully complete a fueling event with all leak check and system purges automated through the FIB control system. The FIB is pre-programmed with a fueling profile which regulates the flow of hydrogen gas as it enters the SFHC. As hydrogen flows through the piping and enters the SFHC CHSS, it increases in temperature. The hydrogen flow is regulated to ensure that tank temperatures remain below the manufacturer’s recommended maximum.

Different fueling profiles can be loaded onto the FIB depending on the tank arrangement and flow regulation necessary to keep the receiving tank temperatures at an appropriate level.

The FIB was initially constructed (Figure 11) and tested as a proof of concept for achieving project performance goals. ZEI engineers were able to quickly take this benchtop prototype and design and build a lighter, more compact, and portable body system, which was used for the demonstration. With the final FIB build commissioned (Figure 12), ZEI conducted multiple tests including the fueling of a Toyota Mirai, fueling the hydrogen pressure vessels being used on the SFHC, and finally a field test with a ZEI partner wherein the FIB fueled a fuel cell commercial truck supplied by a tube trailer.

Figure 11: FIB Initial Build



Source: Zero Emission Industries

Figure 12: FIB Commissioning

Source: Zero Emission Industries

Mobile Refueling Truck (MRT)

The MRT is a mobile hydrogen storage system based on the platform of a Ford F350 Super Duty pickup truck used to transport hydrogen fuel (Figure 13). ZEI modified the original truck to protect and carry hydrogen pressure vessels and a fuel panel which ZEI designed and built.

Initial modifications to the truck included removing unnecessary components and materials. A standard truck mounted lift gate came as a part of the truck and had to be removed to allow for the weight of new components on the truck suspension. The original truck bed was made of wood planks, which ZEI removed to provide access to the underbody of the truck for tank mounting.

Figure 13: Hydrogen Tank Array Installation

Source: Zero Emission Industries

The pressure vessels mounted on the truck are two Hexagon Composites 950 bar hydrogen tank arrays. The tank arrays came mounted in a frame with standardized shipping container connection points. The arrays are fastened at each corner to twist locks mounted to the body of the truck. A new truck bed was installed by ZEI to accommodate the tank array mounts and provides an extra layer of protection from debris that may kick up from the road. Finally, aluminum sheets were fastened to the sides and top of the tank arrays to provide protection from road debris.

With the tanks mounted, the ZEI team designed, constructed, and installed a fueling panel that facilitates safe and easy fueling. The system consolidates the outlets for each tank array into a single fueling port and includes additional instrumentation and breakaway with a hose and J2600 standard nozzle attached. The breakaway will safely shut off the flow of hydrogen if the hose is detached from the truck in an upset condition, like the boat pulling away from the truck while the hose is still attached.

The commissioning of the system included initial pressure and leak testing of individual sub-systems followed by a purge and initial fill of the complete system following manufacturer recommendations.

With commissioning completed the entire system was ready for testing. Testing for the MRT included initial on-road testing of driving routes with minimal public exposure, traversing road conditions that may be experienced in the mission of the MRT and frequent leak checks throughout regular operation. ZEI continued to monitor for leaks regularly throughout the completion of the project.

Emergency Fuel Tank (EFT)

The EFT is a mobile tank of hydrogen which is used to provide low volume hydrogen to consumers. The value of the EFT comes from being able to conveniently store hydrogen for use while in an emergency scenario when a system's hydrogen is fully depleted. ZEI put particular emphasis on simple and safe design to allow operation by any individual with limited training on the system. The EFT can be fueled from the MRT through the FIB.

Procurement of a low volume, low weight, and relatively low-cost hydrogen pressure vessel for the EFT was a challenge throughout the development of the project. To deliver an impactful amount of hydrogen in full depletion scenario, ZEI set a capacity goal for the EFT of 1 kg. To achieve this metric and remain mobile for use in off-road scenarios, ZEI used type IV pressure vessels for their superior weight and volume to capacity ratio compared to the industry alternatives. ZEI investigated custom manufacturing of a pressure vessel to fulfill the needs for the EFT but quickly discovered that individual orders would be prohibitively expensive for use in the project, and likely adoption in the industry. Like with the fuel cells selected for the project, ZEI turned to the light-duty automotive hydrogen market for procurement of the EFT tank. The high manufacturing quantity and market availability allowed ZEI to acquire and modify a light duty tank for use on the project.

The EFT commissioning and testing followed a similar two phase approach to the MRT. ZEI administered the pressure test, incrementally increasing system pressure by approximately 100 bar up to 700 bar checking for leaks. Next, the system underwent an initial purge and first fill. For the purposes of fueling the SFHC, the EFT utilizes the FIB to regulate the release of pressure, ensuring safe operations. With the EFT commissioned, every project system was prepared for use during the demonstration period.

Technology Demonstration

The project technology demonstration entailed the operation of the SFHC in various commercial harbor craft use cases in northern and southern California. The operational profile of the demonstration use cases were developed through research on route and average operating speed of currently in-use harbor craft at each respective demo site.

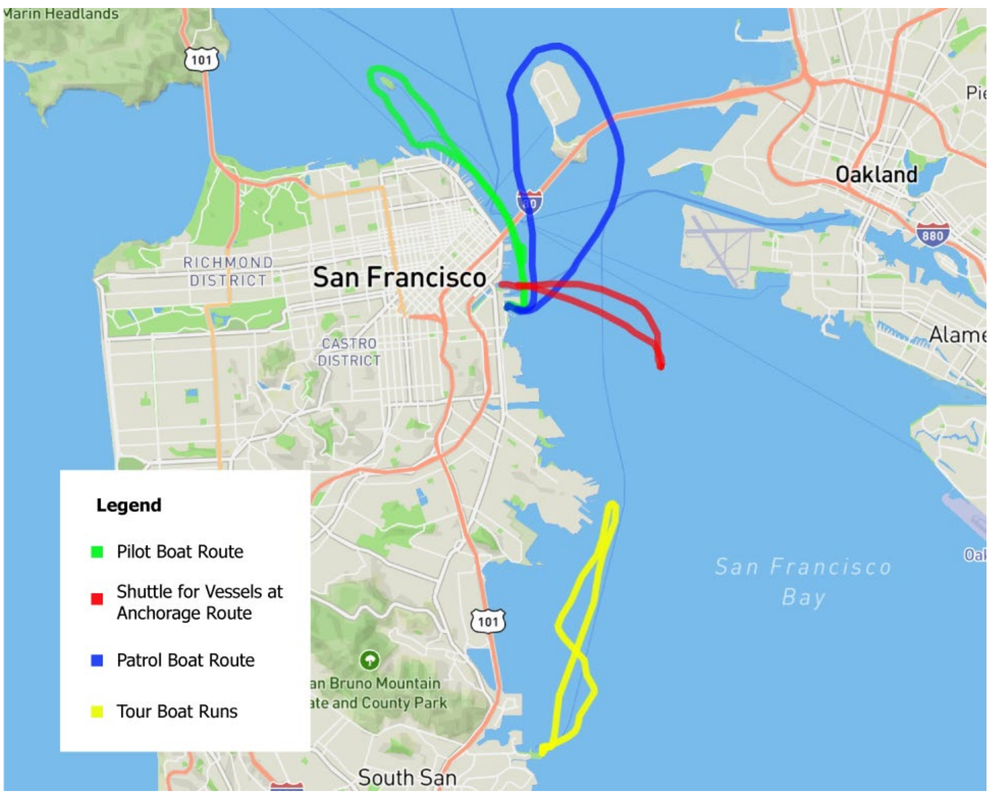
The vessel uses replicated by the SFHC include pilot boat, shuttles for vessels at anchorage, patrol boats, and tour boats. Table 3 represents the average speeds and range for each use case. Figure 14 and Figure 15 display GPS data of a single run from each use case captured during Northern and Southern California demonstrations of the SFHC. Green routes are pilot boat runs, red are shuttle for vessels at anchorage runs, blue are patrol boat runs, and yellow are tour boat runs.

Table 3: Target Commercial Use Cases

Use Case	Range (nm)	Speed (knots)
Pilot Boat	5.5 - 10	16 - 28
Shuttle for Vessels at Anchorage	6 - 8	22 - 32
Patrol Boat	8 - 13	10 - 40
Tour Boat	4 - 9	6 - 18

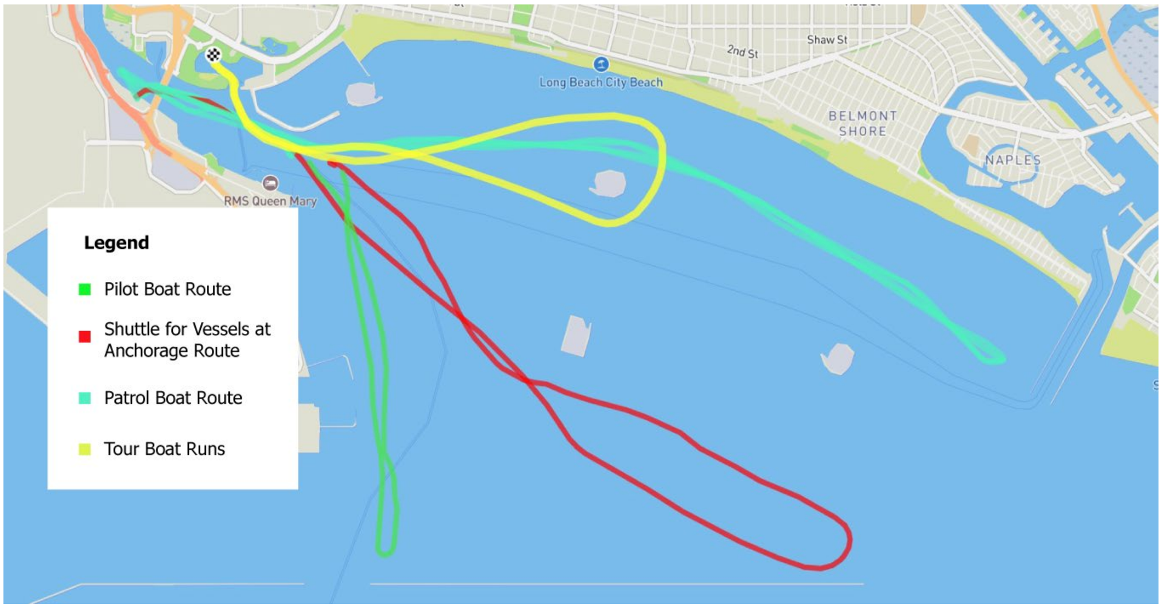
Source: Zero Emission Industries

Figure 14: Northern California GPS Data for Each Use Case



Source: Zero Emission Industries

Figure 15: Southern California GPS Data for Each Use Case



Source: Zero Emission Industries

Throughout the demonstration period, ZEI collected power system, vessel operation, and hydrogen system performance data. Data was collected through automated on-board data capture as well as manual entry logs completed by the ZEI team and vessel operators.

To understand the performance of the project refueling equipment, ZEI analyzed tank data captured by the SFHC control system. Captured fueling data included tank temperatures, tank pressure, and fueling duration. Manual logs tracked any safety events that may have occurred during fueling. Captured data was analyzed to ensure tank temperatures remained below the desired level and to understand how different fueling conditions impacted the SFHC fueling rate.

CHAPTER 3: Results

The completion of the demonstration period for the Small Fast Multi-Use Harbor Craft Project resulted in the final specifications of the demonstrated technology as well as the collection and analysis of performance data. In addition, technology/knowledge transfer activities were completed to bring awareness to the project's goals and activities.

Small Fast Harbor Craft Final Specifications

Table 4 shows performance and physical specifications of the SFHC. Figure 16 depicts members of the project operating the SFHC in the San Francisco Bay.

Table 4: Specifications of the Small Fast Harbor Craft

Specification	Small Fast H2FC Harbor Craft
Vessel type	Harbor Craft
Length	27 feet
Beam	8 feet 3 inches
Propulsion	Sterndrive
Prop Pitch	24 inches / revolution
Hull construction	Fiberglass
Total Weight	5,800 lbs
Hydrogen System Weight	2,850 lbs
ICE System Weight Comparison	1,250 lbs increase
Service speed	25 knots
Max Speed	44 knots (50 mph)
Onboard Fuel Storage	9.7 kg
Fuel Type	Gaseous Hydrogen
Fuel storage pressure	700 bar
Range at service speed	55 nautical miles
Propulsion system power	250 kW

Source: Zero Emission Industries

Figure 16: SFHC Final Build

Source: Zero Emission Industries

Refueling Systems Specifications

Table 5 shows the physical specifications for the MRT. Figure 17 shows a picture of the completed build and the MRT with a picture of the fueling interface located on the back of the truck.

Table 5: Mobile Fuel Truck Specifications

Category	Value
Service Pressure	950 bar
Hydrogen Storage Capacity	50 kg
Total Tank System Weight (empty)	2,500 kg
Total Tank System Frame Dimensions	126.5 in. x 52.0 in. x 60.2 in.

Source: Zero Emission Industries

Figure 17: MRT Final Build

Source: Zero Emission Industries

Table 6 shows the physical specifications of the FIB. Figure 18 depicts photos of the completed build.

Table 6: Fuel Interface Box Specifications

Category	Value
Fill Pressure	Up to 1,000 bar
Dimensions	29in. x 15 in. x 27 in.
System weight	132 lb

Source: Zero Emission Industries

Figure 18: FIB Final Build

Source: Zero Emission Industries

Table 7 shows physical specifications for the EFT. Figure 19 shows the final build of the EFT.

Table 7: Emergency Fuel Tank Specifications

Category	Value
Storage Pressure	700 bar
Storage Capacity	1 kg
Dimensions	51 in. x 24 in. x 20.5 in.
System weight	138 lb

Source: Zero Emission Industries

Figure 19: EFT Final Build

Source: Zero Emission Industries

Demonstration Data Analysis

The SFHC is equipped with four control area network (CAN) busses which collect data from different SFHC powertrain and boat subsystems. This system is summarized in Table 8 and provided the primary data sets for analyzing performance of the SFHC. Data captured by the ZEI team was aggregated and sent to the University of California Irvine's Advanced Power and Energy Program team for independent analysis.

Table 8: Summary of SFHC CAN Bus Systems

CAN Name	Powertrain and Boat Subsystems
CAN A	Electric motor, AC/DC inverter, and DC/DC converter
CAN B	Fuel Cells 1 & 2
CAN C	Boat instrumentation and NMEA2K
CAN D	DC Battery and boat bilge pumps

Source: Zero Emission Industries

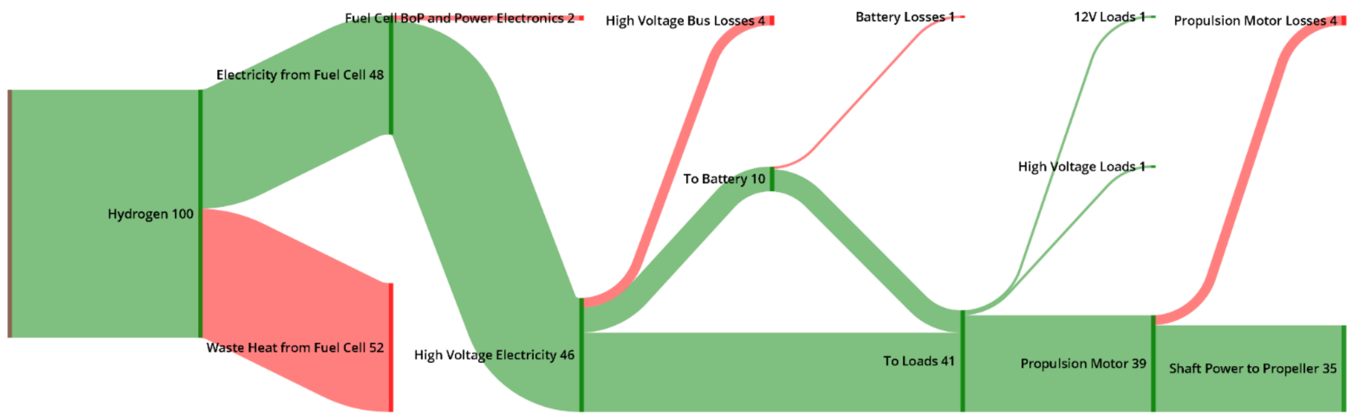
Data from these CAN systems were collected and used to develop various calculations used to evaluate boat performance. These calculated values provide important system performance values that directly address the data collection goals of the project.

Vessel operation was measured from March 3, 2024, to November 21, 2024, covering 24 events—13 in San Francisco Bay and 11 near the San Pedro ports. Total testing time exceeded 80 hours, with the vessel traveling 217 nautical miles (nm) (127 nm in San Francisco Bay and 90 nm near San Pedro). Over the course of the demonstration, the vessel used 63.4 kg H_2. The resulting cumulative fuel efficiency during the entire demonstration was 3.42 nm/kg H_2, or 3.47 nm/gallon gasoline equivalent[13]. This value is specific to the overall demonstration and does not necessarily capture fuel consumption for a specific duty cycle or vessel speed.

Average energy use across the vessel is documented in Figure 20. This figure shows a Sankey diagram tracking energy flows throughout the vessel, starting with hydrogen fuel input, and terminating in end uses and losses. Energy flows are based on cumulative vessel operation. Data collected from the vessel show that 35 percent of hydrogen fuel input is translated to propulsion power from the vessel propeller. Assuming an equivalent diesel engine operates at 33 percent efficiency, a similar boat would require approximately 45 percent more fuel and . cause the rejected heat from the engine to increase from 52 percent to 97 percent. Tracking the conversion of hydrogen to propulsive power, the largest source of loss is the conversion from hydrogen to electricity. Fuel cell conversion losses are an order of magnitude higher than any other type of loss across the entire vessel powertrain.

[13] Conversion of hydrogen to gasoline equivalent used a conversion factor of 1 kg H2 ≈1.016 gasoline gallon equivalent, which is based on the lower heating value of fuels and a gasoline density of 2.82 kg/gallon.

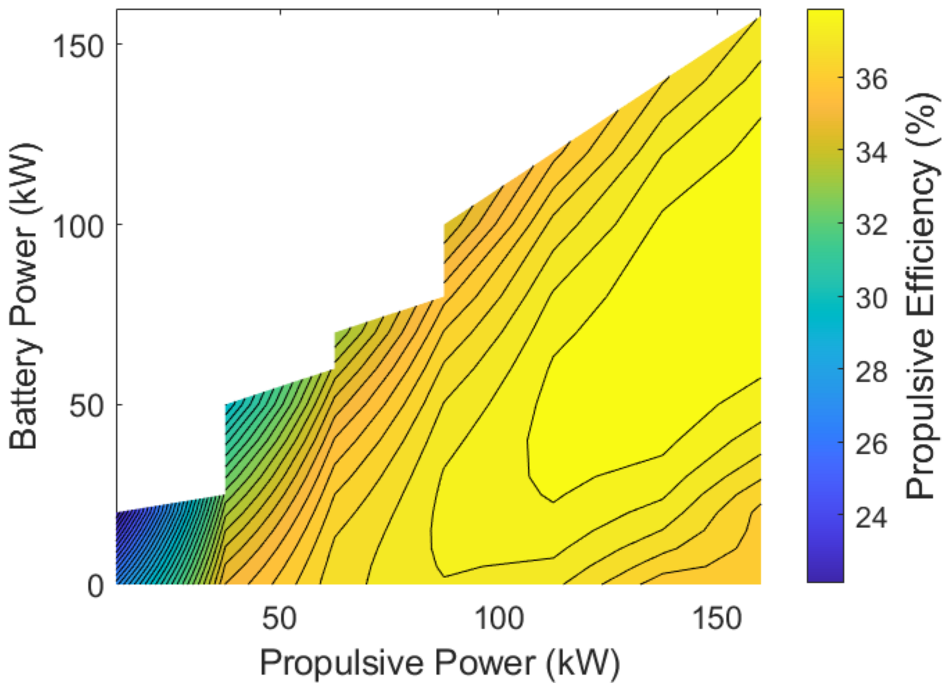
Figure 20: Sankey Diagram Tracking Energy from Hydrogen Flowing into the Fuel Cell, to End Uses and Sources of Loss throughout the Vessel. Units are Percentage of Total Hydrogen Fuel Stored on the Vessel.



Source: UC Irvine, 2025, Generated using https://sankeydiagram.net

Vessel propulsive efficiency across a wide range of propulsive power demands is shown in Figure 21. This figure displays results as a function of battery power supplied to the vessel high voltage DC bus. These results are based on individual component efficiencies, including the two fuel cells, battery, propulsion motor, and the power electronics and other loads necessary to operate the vessel.

Figure 21: Vessel Powertrain Efficiency as a Function of Propulsive Power and Battery Power Supplied to the Propulsion Motor



Source: UC Irvine, 2025

Figure 21 results show that the overall vessel efficiency is consistently above 34 percent when propulsive power exceeds 80 kW. Peak efficiency occurs when:

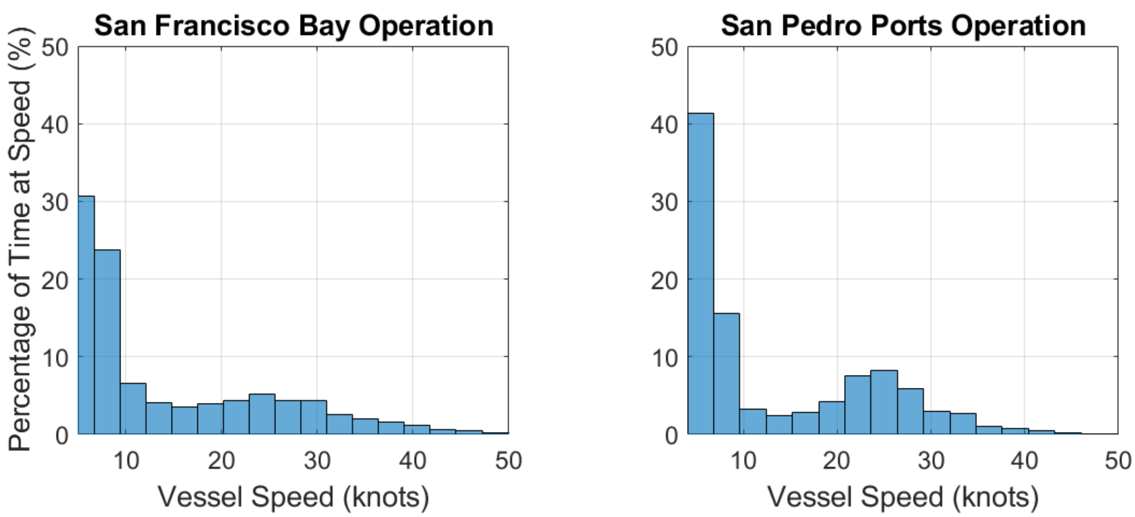
- Propulsion motor speed is > 1,500 RPM, or where propulsion motor efficiency approaches and exceeds 90 percent
- 60 percent to 75 percent of electric demand is met directly by the two fuel cells
- Electric demand is split evenly between the two fuel cells, allowing the systems to operate at a higher stack voltage while keeping fuel cell balance of plant loads lower

Operating the vessel at lower motor RPMs and/or using the battery to meet vessel electrical demand almost always leads to lower propulsive efficiency.

Propulsive power result limits are based on fuel cell capacity of approximately 160 kW – battery power is always required above 160 kW propulsive power. However, at this level of demand, propulsive efficiency stays relatively consistent at approximately 35 percent.

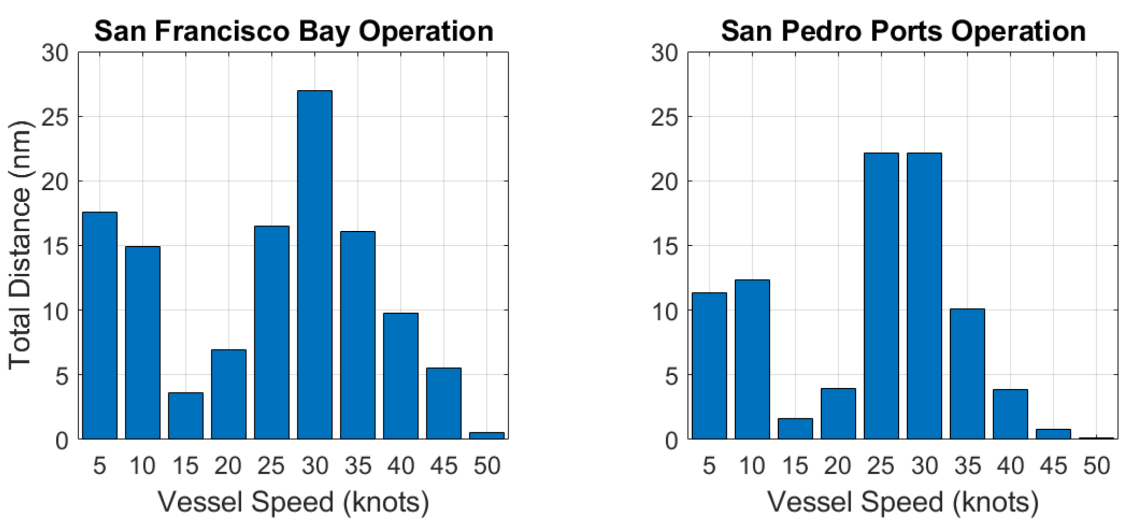
Figure 22 presents histograms of vessel speed. Figure 23 shows the total distance traveled by vessel speed. GPS data confirms the vessel can reach its rated speed of 45–50 knots, though most operations occurred at lower speeds. This was due to test runs for system troubleshooting in San Francisco Bay and speed limits in both locations. After initial testing and troubleshooting was complete, and once outside restricted zones, the vessel typically cruised at 20–30 knots (Figure 22). For example, $3/4^{ths}$ of total distance covered by the vessel occurred at speeds approaching or exceeding 20 knots (Figure 23). This operation speed meets or exceeds operator performance needs for all vessel types demonstrated during the project.

Figure 22: Histogram of Vessel Speed Greater than 5 Knots when Operating in the San Francisco Bay Versus Around the San Pedro Ports



Source: UC Irvine, 2025

Figure 23: Total Distance Traveled by Vessel Speed



Source: UC Irvine, 2025

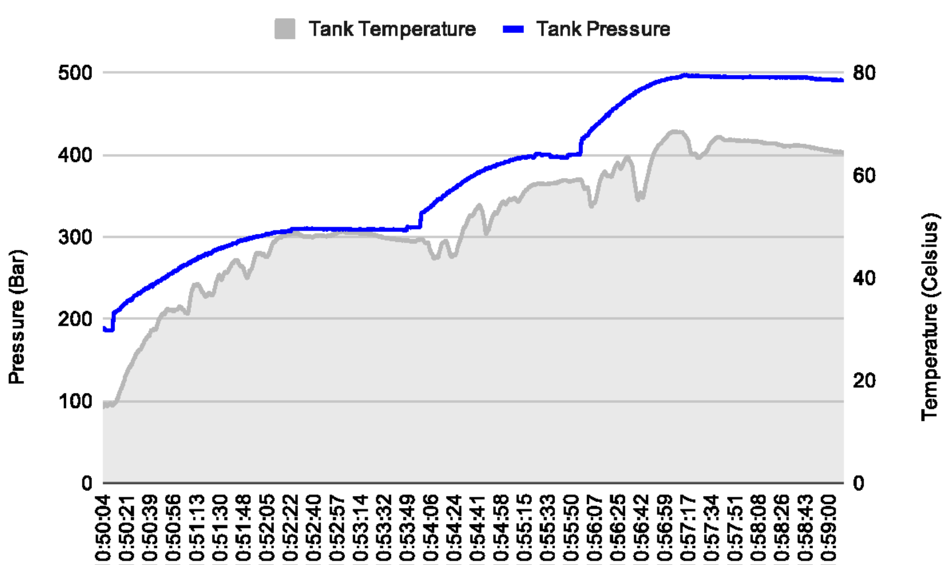
Fueling Performance

Data on fueling events for the SFHC during the demonstration period come from temperature and pressure sensors located on the boat's CHSS and captured through the CAN. All fueling events were conducted with source from the MFT and regulated by the FIB. No recorded events were conducted with the EFT.

Hydrogen fuel used for the demonstration was sourced from local medium/heavy-duty and light-duty fueling stations. The heavy-duty California Energy Commission funded First Element Fuels station located at the Port of Oakland served as a critical source of reliable high-pressure fuel throughout the demonstration period. Fueling events were successfully conducted in locations across California, highlighting the flexibility afforded to operators of this mobile equipment.

The refueling technology developed and used to fuel the SFHC performs cascade fills, a refueling method that utilizes the pressure from a series of high-pressure storage tanks to transfer gas to a receiving fuel tank. During a fill, the FIB regulates flow from the MRT tanks to avoid excessive temperature that could result in damage to the SFHC's storage tank. The average fill mass recorded during the demonstration was 4.62 kg. The average time spent filling was 11 minutes and 23 seconds. The largest fill was 7.67 kg with the smallest being 3 kg taking 28 minutes 59 seconds and 5 minutes 18 seconds, respectively. The highest temperature recorded during a fill was 82 degrees Celsius, 3 degrees within the manufacturer 85 degree limit. The onboard tank was filled to an average mass of 8.18 kg of the 9.8 kg of available storage. Figure 24 graphs the temperature and pressure of a 4kg fuel transfer conducted on November 14th with a fill time of 7 minutes and 19 seconds and a maximum temperature of 68 degrees Celsius.

Figure 24: SFHC Temperature and Pressure During a Fill



Source: Zero Emission Industries

Due to the in-the-field nature of these fueling events, a multitude of environmental conditions played a part in creating variability between filling results. For example, operator performance impacts fill times depending on the speed at which bank switches between tanks on the MRT are conducted. Furthermore, ambient temperature and initial temperature of source and receiving tanks impact maximum temperature, speed, and mass of a fill. The starting pressure of the MRT tanks also plays a critical role in the speed, temperature, and total mass delivered for a fueling event. A reliable source of 950 bar hydrogen would allow the project team to fill MRT to its maximum pressure and regularly conduct a more complete fill on the SFHC. These conditions affected the refueling performance during the testing and demonstration period.

Given the resources to reliably isolate environmental variables and increase data instrumentation, ZEI would be interested in understanding the optimization of hydrogen cascade fills for commercial use cases. Certain environmental scenarios were observed during the demonstration that could lead to faster fill times. For example, fueling events conducted soon after operation of the SFHC would have significantly lower initial tank temperatures than those conducted before or long after operation. Investigation on how fills conducted during operating hours reliably lead to reduced fill times through increased flow rate while remaining below maximum operating temperatures could support commercial pathways to hydrogen adoption.

Additional componentry on MRT and FIB such as compressors or chillers could be leveraged to drive down fill times and increase total fill mass for fueling events, but it should be noted the addition of such componentry would affect reliability. One of the significant successes achieved by the demonstration technology was the 100 percent success rate of hydrogen fuel transfer regardless of environment and fueling scenario. Based on learnings from technology transfer engagements and market trends, the project team believes enablement of more reliable and cost-effective fueling at the cost of improved fill time or mass transfer is an appropriate trade for early adoption of hydrogen technology.

The hydrogen refueling technology developed for the Small Fast Multi-Use Harbor Craft Project successfully fueled the SFHC through the demonstration while maintaining the safety of operators and equipment. While further optimization could reduce fill times, the demonstration period clearly validates the project technology as mobile and reliable solutions for gaseous hydrogen refueling.

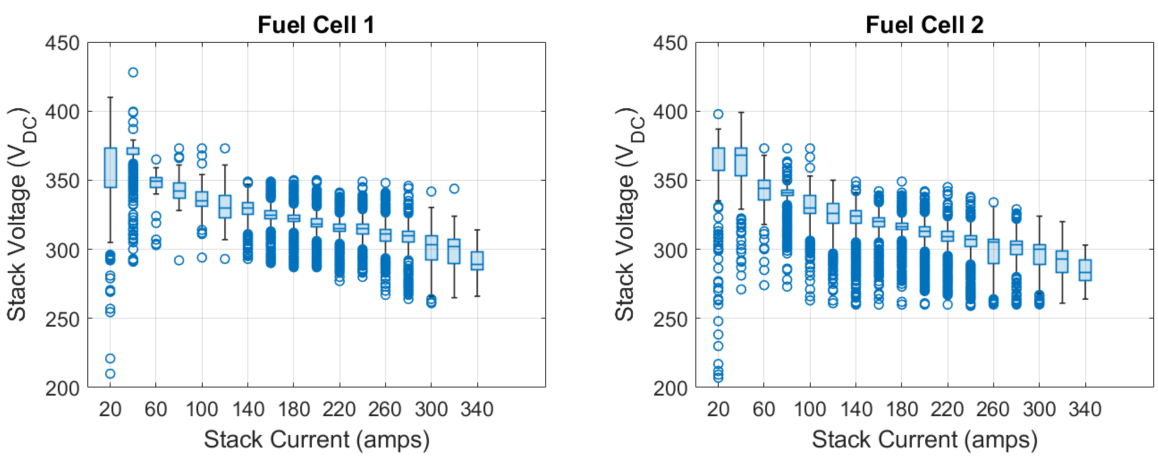
Powertrain Component Performance

This section analyzes the performance of the fuel cells, battery, and propulsion motor. Analysis of the fuel cell system separates between fuel cell stack and system. Stack measurements consider the fuel cell stack only – voltage ampacity measurements are taken at the fuel cell stack electrical terminals. Fuel cell system measurements include the fuel cell stack, the air compressor supplying air to the fuel cell system, fuel cell coolant system pumps, and DC/DC rectifier connecting the fuel cell system to the vessel high voltage bus.

Fuel cell 1 and 2 stack efficiency during the demonstration was 48 percent and 47 percent, respectively, on a higher heating value basis. Electricity output from the stacks is used to power the fuel cell cooling systems and air compressor before being boosted to a higher DC voltage. Fuel cell system efficiency accounting for the cooling system and air compressor loads, plus DC/DC conversion losses, was 46.6 percent and 45.9 percent, respectively. In total, the cooling system, air compressor, and DC/DC conversion losses use 2.5 percent - 3 percent of total fuel cell electricity output.

Fuel cell voltage-current curves for both stacks are shown in Figure 25. These figures show box plots for the voltage-current data where the middle line in each box shows the average value, the top and bottom of each box shows the 75th and 25th percentiles, and the whiskers indicate the nonoutlier minimum and maximum values. Outliers are shown using a circle marker[14]. In general, the voltage-current curves show a typical fuel cell voltage-current curve where there is a relatively steep decrease in voltage at low ampacities due to electrochemical activation losses, followed by a steady decline in voltage associated with ohmic/ion transport losses. The figure shows that this decrease in voltage with increasing ampacity becomes larger at higher ampacities, indicating a drop in voltage due to reactant concentration limitations at the individual cell level and that each stack has a limiting current of around 340 amps.

Figure 25: Voltage-current Results for the Two Fuel Cell Stacks



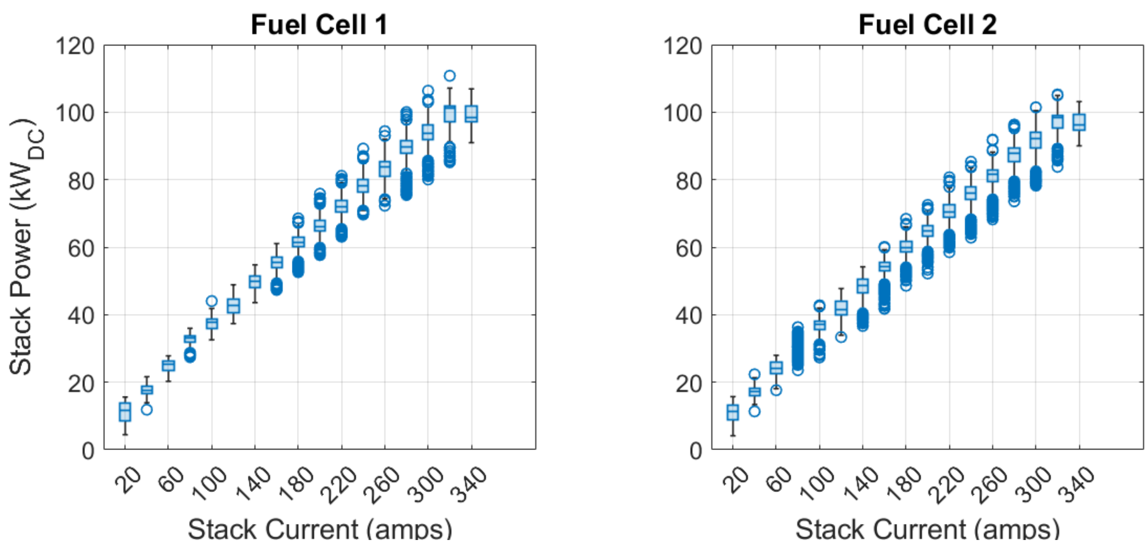
Source: UC Irvine, 2025

Figure 26 shows power versus current results for the two fuel cell stacks. Considering Figure 25 and Figure 26 together support the conclusion that both stacks have a limiting current of 340 amps. Fuel cell stack power peaks at 320 amps and begins to drop off as system ampacity increases. Additionally, these results suggest that ampacity draws from the fuel cell stacks

[14] Outliers are defined as data falling outside 1.5 times the interquartile range. This definition identifies data that is significantly further away from the majority of the datapoints in the set.

should be limited to 300 amps or lower as the higher current does not lead to higher stack output.

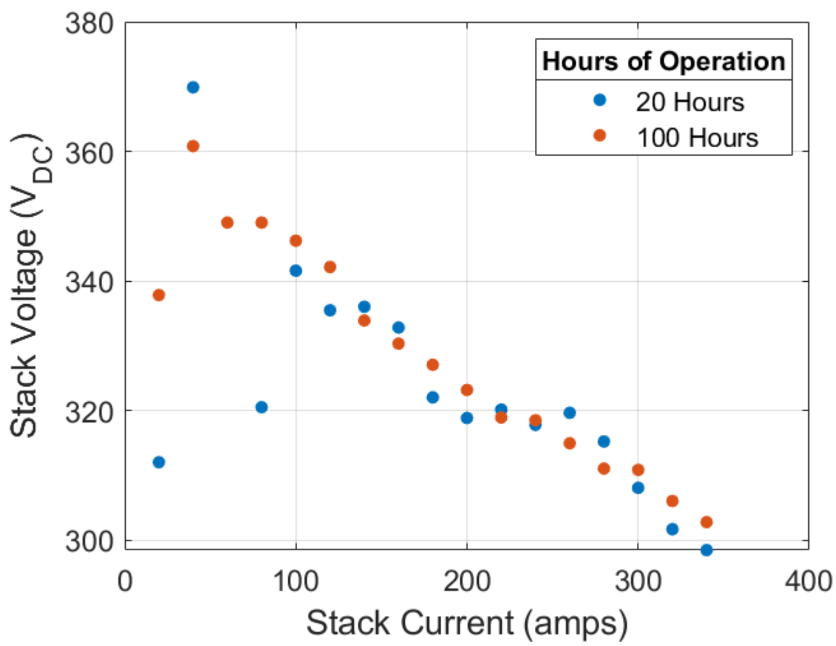
Figure 26: Power-current Results for the Two Fuel Cell Stacks



Source: UC Irvine, 2025

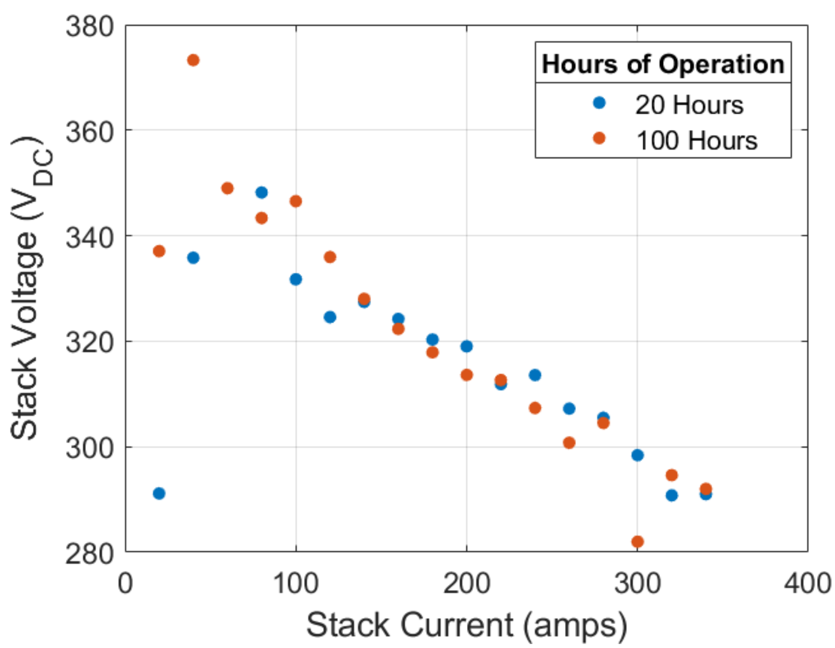
An additional consideration during vessel demonstration is fuel cell stack degradation. Figure 27 and Figure 28 show the stack voltage-current curves for fuel cell 1 and 2, respectively. These charts show this curve after 20 hours of operation and 100 hours of operation. The data show that both stacks experienced minimal to no degradation during the demonstration project. Note, however, that 100 hours is insufficient for examining long-term degradation of a commercially available fuel cell stacks. These results are positive, but additional measurement and verification is required to understand the long-term performance of the stacks.

Figure 27: Voltage-current Results for Fuel Cell 1 at 20 and 100 Hours of Operation



Source: UC Irvine, 2025

Figure 28: Voltage-current Results for Fuel Cell 2 at 20 and 100 Hours of Operation



Source: UC Irvine, 2025

Analysis of the battery system is limited to calculating round trip efficiency (energy delivered versus energy stored) and the voltage – current characteristics of the system. Over the course of the demonstration, 25 percent of the electricity eventually sent to the propulsion motor, 12V loads, and other high voltage loads passed through the battery. During this operation, the battery operated with a round trip efficiency greater than 92 percent. This value is substantially higher than typical battery round trip efficiencies of 85 percent to 90 percent. However, the battery system maintained a high round trip efficiency due to the lack of AC/DC conversion by integrating directly into the vessel high voltage DC loop.

Vessel Safety

Throughout the SFHC demonstration ZEI kept a log to capture safety related incidents including but not limited to accident or incident descriptions of any direct or near misses related to SFHC demonstration or the demonstrated hydrogen refueling infrastructure. Throughout the completion of the demonstration phase no safety incidents occurred and thus, no logs were recorded.

This can be primarily attributed to the ease of use of the technology. The reliability of the refueling technology developed in this project enabled operators to comfortably and reliably fill the SFHC throughout its demonstration. The potential of human error was minimized through the system designs, ensuring software prompts and easy to follow instructions accompanied all operations. The familiar operating instruments of the boat such as a steering wheel, throttle, and NMEA 2000 navigation display meant captains of the vessel were not overburdened by unfamiliar controls.

Vessel Maintenance

ZEI documented seven maintenance events during the demonstration project. Of these seven events, three were unscheduled. The unscheduled maintenance events included:

- **Replacing the power steering fluid pump:** Prior to 7/22/24, the vessel steering wheel was left at a hard stop for too long, causing the power steering fluid pump to fail. The pump was replaced. Replacement took four hours to complete. No subsequent issues with the power steering fluid pump occurred during the demonstration.
- **Replacing the spherical bearing in the stern drive:** ZEI noticed an unexpectedly high noise level coming from the original sterndrive during May demonstration runs. The team performed a drivetrain inspection and replacement that spanned 6/28/24 – 7/16/24. During initial inspection, technicians and engineers found that the spherical bearing in the transom plate in the stern drive was close to failure. As a result, the sterndrive was replaced with an improved drive (the Mercuiser Bravo III). The total downtime during event lasted 18 days, but if parts were on hand and inspection was not necessary, the maintenance event would take a trained team 3 days.
- **Tank valve replacement:** Prior to 10/27/24, vessel operators noticed that there was insufficient hydrogen flow through the tank valve at low tank pressures. ZEI technicians

and engineers diagnosed the tank valve, identified an issue with the built-in excess flow valve, and replaced the valve. The replacement took three days.

The four scheduled maintenance events included:

- **Drive train inspection:** Technicians and engineers spent four days starting 7/6/24 disassembling the vessel powertrain to inspect each individual component. The scheduled maintenance was caused due to unexpected noise at low and high motor speeds. All drivetrain components appeared to be in good working order. The inspection then resulted in examining the stern drive, leading to the unscheduled replacement of the stern drive listed in the 2nd bullet under "unscheduled maintenance events".
- **Installation of electronic trim tabs**: On 7/8/24, electronic trim tabs were installed on the vessel. This occurred because operators found it more difficult to get the vessel onto a plane with the new system having more weight in the aft of the boat than the original system. Operators reported the vessel performed much better after trim tab installation and was comparable to the stock boat. Trim tab installation took seven hours.
- **Cooling system optimization**: On 7/29/24, ZEI technicians and engineers reworked parts of the vessel powertrain cooling system to make it easier to maintain the overall vessel. Modifications focused on shortening coolant hose runs. Total maintenance occurred over the course of three days.
- **High pressure hydrogen piping modifications**: Prior to 7/19/24, the hydrogen storage system lacked an analog pressure gauge on the high-pressure side. The system has an electronic pressure transducer, but line pressure could not be verified unless the boat was turned on. A pressure gauge was installed to allow determination of line pressure in any situation. In addition, an isolation valve was installed on the high pressure refueling line as a redundant way to isolate hydrogen from the refueling port while the vessel was operating. Both actions improve the overall safety of the system. These modifications took three days to install and leak test.

Operator Experience

Three vessel operators responded to a survey asking about vessel performance compared to operating similar boats that use a reciprocating engine powered with fossil fuel. The operator experience with the vessel has been largely positive, with users highlighting both the performance benefits and areas for improvement.

The FCV Vanguard demonstrated performance characteristics similar to ICE boats, with key advantages in acceleration, maneuverability, and noise reduction. Operators particularly appreciated the ability to make refined speed adjustments, the quiet operation, and the increased safety features.

While the feedback was largely positive, some areas for improvement were mentioned. Operators noted that the volume of data available through the drive system interface was higher than in ICE boats, which could require some adjustment. Additionally, further refinements in handling and throttle response could enhance operator familiarity and ease of use.

While some differences in interface and handling require adaptation, the overall feedback suggests that fuel-cell-powered marine vessels offer a compelling alternative to conventional ICE-powered boats.

Total Cost of Ownership

A total cost of ownership (TCO) approach was used to assess the potential economics of hydrogen fuel cell vessels of the size and power rating of the Vanguard. Table 9 and Table 10 show the technical and economic parameters used in the analysis. Drive train costs are based on a fuel cell versus diesel vessel cost analysis by Gaurav et al.[15] The numbers in Table 7 of that report were adjusted using a currency conversion of 0.95 dollars per Euro and escalating 7 percent from 2022 to 2024 dollars. Based on prior learning-curve analysis by the University of California, Irvine (UCI), and consistent with US Department of Energy (DOE) targets, the fuel cell system cost, storage cost, and battery cost are projected to be 70 percent, 40 percent, and 35 percent lower, respectively in 2035. The values in the reference are in Euros from sources in the 2021 to present timeframe.

The estimated fuel economy of the Vanguard operating at 25 knots is 6.28 nm/gallon gasoline equivalent providing a 55 nm range with the 9.8 kg on-board storage. A web search of fuel consumption for boats of similar size and engine power yielded an average fuel economy at 25 knots of 3.64 nm per diesel gallon.[16] This gives an estimated energy requirement (EER) of 1.73. The California LCFS program specifies an EER of 1.9 for a fuel cell electric truck relative to a reference diesel powered truck.[17] The vessel-data value of 1.73 was used as the base value in the TCO analysis. That ratio is used in the TCO to estimate fuel consumption for two duty cycle cases that differ from the Vanguard see trials: a harbor patrol vessel, and an offshore patrol or police vessel. The assumed annual operating hours are 625 and 1,500, respectively and are the mid-points in the ranges provided in Industrial Marine Power Corporation duty-rating descriptions.[18] The harbor patrol vessel is assumed to operate at lower speed averaging 10 knots and the offshore patrol vessel is assumed to operate at an average

[15] Soni, Gaurav, Rui Costa Neto, and Lúcia Moreira. 2023. "Hydrodynamic Simulation of Green Hydrogen Catamaran Operating in Lisbon, Portugal." *Journal of Marine Science and Engineering* 11 (12). https://doi.org/10.3390/jmse11122273. Table 7.

[16] https://kokeilu20110920.wordpress.com/fuel-economy-of-25-29-feet-boats/ Average of 4 vessels with 260 HP engines and cruising speed of around 25 knots.

[17] https://ww2.arb.ca.gov/sites/default/files/2020-07/2020_lcfs_fro_oal-approved_unofficial_06302020.pdf Table 5.

[18] https://www.impcorporation.com/blog/marine-engine-duty-ratings

speed of 30 knots. These equate to average fuel consumption rates for the fuel cell vessel of 1.59 and 7.78 DGE/hr., respectively. Technology costs are drawn from various prior studies by UCI using DOE and NREL projections as well as learning-curve analysis. Dispensed fuel in 2035 uses heavy-duty trucking values projected in a recent NREL analysis.[19] Current cost is based on recent UCI analysis assuming well utilized infrastructure and current infrastructure costs and hydrogen production cost of $6/kg. To reflect the environmental benefit of the fuel cell vessel, the TCO includes a social cost of carbon in using the $190 per MTCO2e social cost recently published by the DOE.[20] Hydrogen is assumed to be 40 percent renewable fraction in 2024 and 100 percent in 2035. Fuel costs are estimated from prior UCI analysis.

Table 9: Fixed Parameters for TCO Analysis

Base Parameters for TCO Analysis	
Total Engine Power (kw)	200
Fuel Storage (kg-H2)	10
Battery Capacity (kwh)	25
FC Vessel Fuel Use at 25 knots (Measured) (DGE/hr.)	6.28
Harbor Patrol Use Case Annual Operating Hours	625
Offshore Patrol Use Case Annual Operating Hours	1,500
EER	1.73
Financing Rate (annual percent)	6 percent
Financing Period (years)	10
Social Cost of Carbon ($2024)	191

Source: UC Irvine, 2025

Table 10: Current Versus 2035 Cost Parameters for TCO Analysis (2024 Dollars).

	H2-FC		**Diesel**	
Parameter	**2024**	**2035**	**2024**	**2035**
Fuel Cell System + Motor $/kw	$1,365	$410	n/a	n/a
Battery System $/kwh	$135	$88	n/a	n/a
Hydrogen On-board Storage $/kg	$740	$445	n/a	n/a
Drive Train and Storage Capex	$284,000	$85,200	$71,600	$71,600
Fuel Cost	$16	$8	$4	$5
CO2 kg/DGE	6	0	10	10

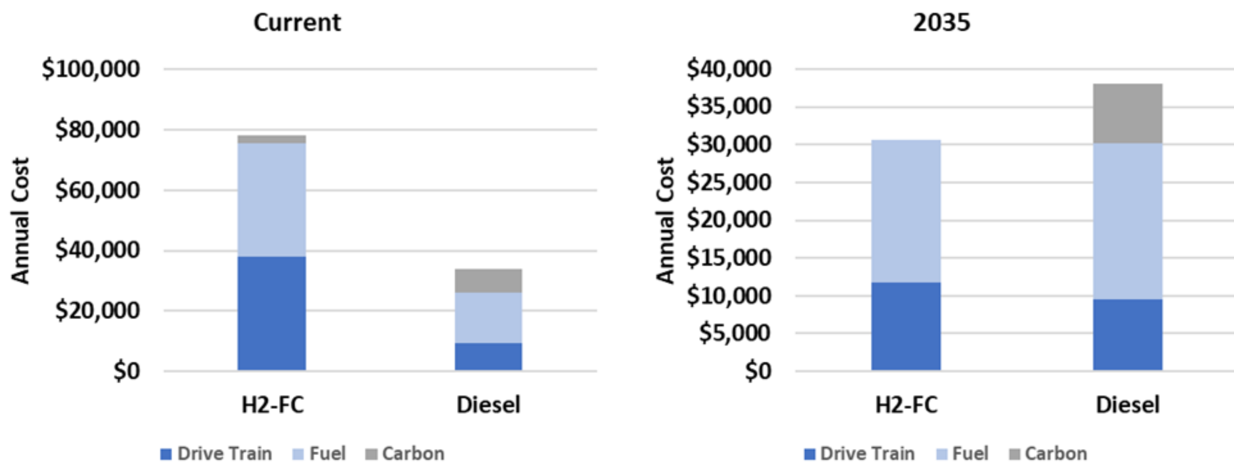
Source: UC Irvine, 2025

[19] Bracci, Justin, Mariya Koleva, and Mark Chung. 2024. Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-88818. https://www.nrel.gov/docs/fy24osti/88818.pdf.

[20] EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances, November 2023.

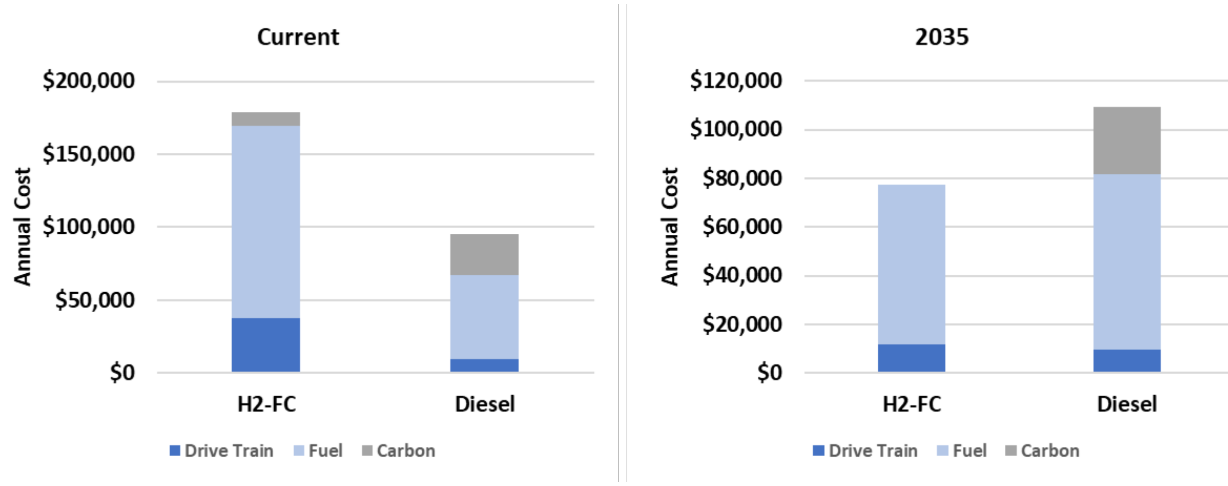
The TCO comparisons for the two use cases are shown in Figures 29 and 30. In each case, fuel is the dominant expense with the fuel cell vessel showing significantly higher cost in 2024 but showing slightly lower cost in 2035.

Figure 29: Fuel Cell versus Diesel Harbor Patrol Vessel TCO Comparison.



Source: UC Irvine, 2025

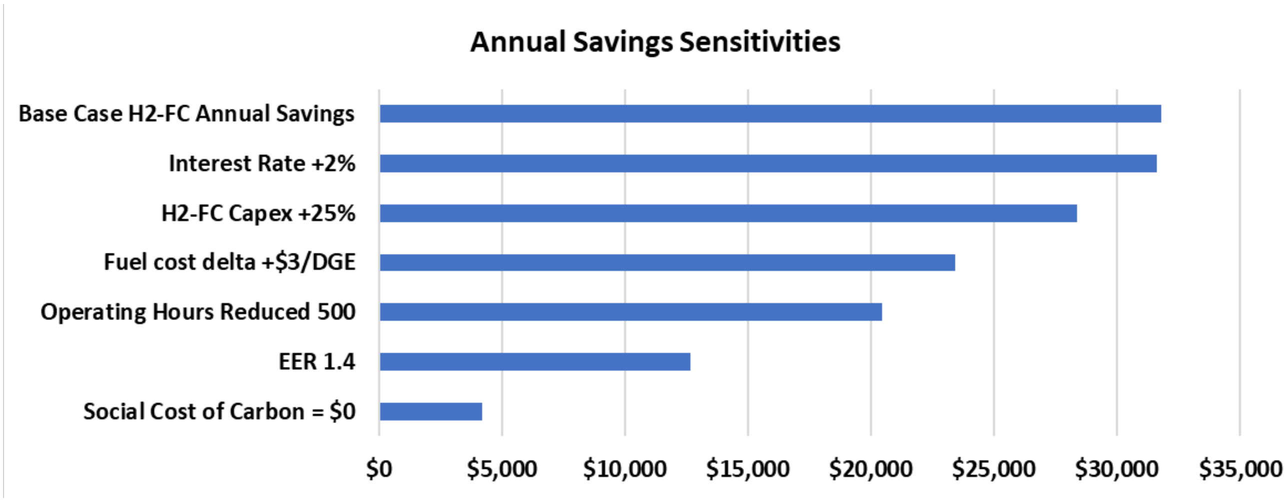
Figure 30: Fuel Cell versus Diesel Offshore Patrol Vessel TCO Comparison.



Source: UC Irvine, 2025

Figure 31 shows the change in annual cost difference for the offshore use case from the base-case values described in Table 9 above. The base-case annual savings are $31,800 which is 29 percent lower than the diesel case. The sensitivity assumptions listed in Figure 31 are less favorable for the fuel cell case and therefore show reduced savings as noted. The lowest savings are achieved when carbon cost is excluded yielding $4,200 in savings or roughly 5 percent of the diesel-case cost. The fuel cell vessel continues to show TCO savings across all of the sensitivities modelled. The operating cost is dominated by fuel cost, so savings for the fuel cell vessel depends primarily on the price of dispensed fuel, the fuel economy ratio of the vessels being compared, and the annual operating hours for a given duty cycle. Overall, the results show promise that the fuel cell vessel can reach TCO parity by the 2035 timeframe.

Figure 31: Annual TCO Savings Relative to Diesel Case for 2035 Offshore Vessel Case Based on TCO Parameter Changes to Base Case as Noted



Source: UC Irvine, 2025

Challenges and Lessons Learned

Hydrogen Fuel Price and Availability

The Small Fast Multi-Use Harbor Craft project developed novel technology to support mid-stream and end use hydrogen transportation and fuel transfer. Despite the successful deployment of these technologies, hydrogen fuel availability and pricing remained an upstream challenge.

Throughout the development, commissioning, and demonstration portions of the project, hydrogen availability diminished while price grew. Many light duty station developers abandoned established and in-development fueling locations throughout Northern and Southern California as the average price per kilogram of hydrogen went from $16 to $36.

The project development site, located in South San Francisco, saw the removal of all but a single permanent fueling station on the San Francisco peninsula. The remaining station is low capacity and was not used by ZEI to avoid fuel availability disruptions to FCEV drivers in the area.

Hydrogen procurement directly from hydrogen suppliers was investigated by the ZEI team but contract negotiations consistently led to agreement structures, such as take-or-pay with high volume commitments, which were not feasible for a small technology startup like ZEI.

ZEI was able to acquire hydrogen at True Zero fueling locations located throughout CA by coordinating with True Zero on fueling days and times that would not disrupt on-road vehicle drivers. A particular station that came online during the project and reduced much of ZEI's hydrogen availability anxiety was the heavy-duty station located at the Port of Oakland, an effort partially funded by the California Energy Commission. With the installation of this station, a few hours commute in the mobile fuel truck resulted in reliable hydrogen at over 700 bar for all project system testing and demonstrations. In Southern California, new liquid hydrogen supplied True Zero Stations, particularly the one in Costa Mesa, provided the project team with reliable fueling for Southern California demonstrations.

ZEI believes the continued deployment and support of reliable, high volume, high pressure fueling stations in tandem with novel mobile fueling solutions like the ones developed for this project will enable the adoption and expansion of zero emission hydrogen fuel cell technology deployments including but not limited to harbor crafts.

Component Procurement

During the design and development portion of the project, the ZEI team was met with challenges regarding identification of availability, pricing, and lead time for major system components. It should be noted that early in the project, the Covid-19 pandemic impacts caused supply chain issues which temporarily impacted system component procurement but has since primarily been resolved.

Procurement of hydrogen equipment is a complex and resource intensive process. ZEI spent a significant number of hours generating equipment supplier lists to identify the component options that met system requirements. Even with decades of experience purchasing equipment in the hydrogen industry, the project team often had to start at the ground level with equipment suppliers to develop relationships, understand product offerings, collect specifications, understand availability, get pricing, acquire lead times, and more. Without access to readily available system information from suppliers or a central database/marketplace for existing hydrogen equipment, anyone looking to develop a fuel cell powertrain system would have to undergo a similar lengthy procurement process.

For example, procurement of the fuel cell modules for the SFHC took many months and led to a decision by elimination. At the start of the project, ZEI conducted outreach with many fuel cell OEMs to understand system performance specifications. Relationships had to be developed, many of which involved nondisclosure agreements, to acquire initial system specifications. Even with a relationship developed and specifications in hand, understanding of ability to purchase and lead times remained uncertain. Due to the complexity of their solutions, some OEMs determined that the equipment sale would not justify the OEM engineering effort needed to support the SFHC power system development and ended the engagement. Of the OEMs that remained, a majority could not promise lead times that would meet the milestones and timeline of the project agreement or ended with prices outside of the project budget. This unstable purchasing environment will lead to slow adoption for hydrogen fuel cell technology in applications not prioritized by OEMs.

Future hydrogen deployments will meet similar struggles without a pathway to more transparent hydrogen component procurement.

Electric Motor to Sterndrive Coupling

A unique technical challenge which was not considered during the inception of the project involved translating the power of the electric motor to the ICE sterndrive of the boat. Electric motors are rated for extremely tight tolerances while under way, meaning they must maintain a relatively rigid structure with the mechanism they are interfacing with. On the other end of the spectrum, ICE sterndrives have loose tolerances and are designed for lots of play in the system. ZEI conducted in-depth research into solutions available in the market, reaching out to OEMs as well as independent maritime solution providers to understand who else may have solved this challenge. To ZEI's surprise, there were no currently available solutions for mating the tight tolerances of an electric motor to a sterndrive. As a result, ZEI designed a novel coupling system utilized in the SFHC.

The coupling system designed onboard the SFHC is applicable to any electrified system of a similar configuration. Operators looking to repower with battery-only technology would need to solve the same challenge. Regardless of the zero-emission electrification pathway taken, electric motor to traditional sterndrive coupling will remain a challenge.

As the state looks to meet its climate goals, electrified zero-emission commercial harbor crafts will play a critical role. Defining a reliable solution for mating electric inboard motors to existing sterndrives will streamline adoption and enable vessel owners to repower their existing ICE propulsion system.

Technology Knowledge Transfer Activities

Throughout the development and demonstration of the Small Fast Harbor Craft project, the project team engaged in technology and knowledge transfer activities to help engage stakeholders with lessons learned, leading to recognition of hydrogen and fuel cell technology as viable pathways to supporting California's decarbonization goals. ZEI issued two separate press releases throughout the project's development: (1) announcing the launch of the project in Q4 of 2021 and (2) the public unveiling of the vessel under the new name "FCV Vanguard" in Q4 of 2024. In addition, the project team engaged with individuals, public agencies, regulatory bodies, potential technology adopters, and more through active outreach and hosted events.

U.S. Coast Guard (USCG)

ZEI CEO Dr. Joseph Pratt presented to the USCG on hydrogen and fuel cell technology, safety, and marine regulations (Figure 32). Lessons learned from the FCV Vanguard project played a role in crafting the narrative for best practices for hydrogen safety and hydrogen fuel cell viability on the water.

Figure 32: ZEI Visits USCG Headquarters

Source: Zero Emission Industries

Zero Emission Industries Site Visits

On multiple occasions, the ZEI team invited members from public agencies and the private sector to visit their headquarters (Figure 33). These visits involved sharing the technology developed through the project and highlighting real adoption pathways for hydrogen fuel cells. Site visits included engagement with members of SoCalGas, private entities, and individuals such as Dr. Sunita Satyapal, Director for the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cell Technologies Office, as well as members of transit agencies who are looking to transition their fleets to zero emission technology.

Figure 33: Director for the U.S. DOE Hydrogen and Fuel Cell Technologies Office Visit

Source: Zero Emission Industries

Independent Journalist Engagements

While ZEI distributed two press releases for the project, the team continued to engage with journalists and news outlets to further provide lessons learned from the project. These engagements included participation in three podcasts on hydrogen for marine and contributing articles to marine outlets.

FCV Bay Area Launch Event

On the week following the press release for the launch of the FCV Vanguard, the ZEI team held a public launch event (Figure 34). This event was listed as a part of SF TechWeek, bringing together individuals in the technology space, investment space, as well as those simply interested in learning about hydrogen technology. The event had an RSVP list of 154 attendees who all had the opportunity to engage directly with the ZEI team and the technology developed through the project.

Much of the content presented and discussed revolved around education of guests on the core hydrogen narratives enabled by project technology innovations. These narratives include the viability of hydrogen fuel cells as a zero-emission energy pathway for on and off-road heavy-duty applications for new builds and re-powers, as well as how the refueling technology developed from the project significantly simplifies and reduces the costs of safe mobile gaseous hydrogen fueling infrastructure.

Event attendees met these narratives and the presentation of project equipment with overwhelming positivity. Interest in the future productization of the FCV Vanguard's powertrain system was a common topic of discussion often leading to conversations around the different use cases that the prototype system on the FCV Vanguard could potentially power. While ZEI is still in the exploratory stage of where a system like the one developed for this project can additionally be applied, in addition to commercial harbor craft, other applications such as heavy-duty port equipment, on-road medium and heavy-duty trucks, high-performance automotive, recreational boats, and stationary power were all identified as future uses of interest.

Figure 34: FCV Vanguard Launch Event

Source: Zero Emission Industries

Public Engagements and Partner Ride-Along

During the demonstration in Southern California (Figure 35), the ZEI team hosted multiple technology demonstrations to engage with members of the public, project stakeholders, and potential technology adopters. These engagements included the California Energy Commission, SoCalGas, UC Irvine, port equipment operators, port environmental planners, and more. The ZEI team educated guests on the technology developed through the project as well as offered rides to select members to experience the hydrogen fuel cell technology firsthand.

Conversations with the public and individuals with no prior background in hydrogen sometimes led to questions that ZEI has heard and experienced since its inception. These questions revolved around the dangers of hydrogen technology, often unfounded claims around explosion risks, and general fears of hydrogen combustibility. While a 5-minute conversation backed by learnings from this project and ZEI's subject matter expertise often subsided these concerns, it is clear that the general public still requires benefits from education around how hydrogen safety is approached and the real considerations one must take when developing novel hydrogen solutions. The technology developed by this project was a simple and effective way to engage the public on hydrogen fundamentals and ZEI aims to maintain its purpose as both a technology demonstration and educational tool for creating public interest.

Figure 35: FCV Vanguard SoCal Engagements

Source: Zero Emission Industries

Southern California Law Enforcement Engagement

In Southern California, ZEI engaged with members of port security, local law enforcement (Figure 36) and harbor patrol. These engagements were held at the Los Angeles Maritime Law Enforcement Training Center (MLETC) as well as at a local boat launch ramp.

At MLETC, ZEI presented to maritime law enforcement trainers and trainees about the hydrogen powertrain, storage, and safety systems onboard the FCV Vanguard. Later in the day, ZEI showed off the capabilities of the hydrogen powertrain system by joining trainees on the water as they conducted tests in their respective law enforcement training vessels. At the boat launch ramp, ZEI invited active law enforcement members and leadership to ride on the FCV Vanguard and learn about the fueling technology developed for the project.

After completing on the water demonstrations of the vessel, law enforcement was impressed by the silent operations of the FCV Vanguard and expressed how that posed tactical advantages over existing internal combustion engine alternatives. In addition, law enforcement officials recognized the relatively low thermal load of the fuel cells when inspecting the engine bay after operation. They noted that maintenance while underway and briefly after operation is something not considered possible with current powertrain systems due to extreme temperatures, but fuel cells could change that narrative.

Overall, members of law enforcement were extremely interested in the potential of hydrogen fuel cells as a power source for future operations, even highlighting value outside of the zero emission benefits they provide to California’s emission reductions goals. ZEI will continue to engage with these operators and understand pathways to decarbonize their vessel fleets.

Figure 36: FCV Vanguard Law Enforcement Engagement

Source: Zero Emission Industries

ZEI plans to use the FCV Vanguard and its accompanying fueling technologies as a framework for continuing conversations around hydrogen adoption and sharing project learnings well after the completion of the project.

CHAPTER 4: Conclusion

The hydrogen powertrain package onboard the SFHC validates the performance of fuel cells under the heavy demands of small harbor crafts. The refueling systems developed to provide remote gaseous hydrogen infrastructure to the SFHC provide a first step in innovative ways to solve hydrogen supply challenges impacting wider adoption today.

The fuel cell powertrain package developed through the project provides a proof point for a pathway to zero emission alternatives for popular 6.7-liter class of marine diesel engines used across a wide range of harbor craft applications today. Capable of delivering 250 kw (335 HP) of power through the electric motor, the SFHC's powertrain achieves high performance specifications while providing operators with an improved driving experience over a standard ICE. The powertrain system similarly proves viability in non-commercial vessels of a similar power range, potentially removing an additional significant quantity of California's GHG emissions if deployed at scale. The SFHC power package also shows off the potential of fuel cells as a repower solution for existing vessels, further reducing the environmental impact of the transition to zero emission transportation.

While the demonstrated powertrain package is not a complete productized solution, the capabilities of fuel cells are clear in off-road applications. With limited hours on the system, ZEI believes continued operation of the SFHC along with further refinement will help direct vessel operators toward hydrogen as a zero-emission solution for their commercial purposes. The cost of hydrogen is a majority of a commercial vessel's total cost of ownership. Reducing this cost is critical to overcome higher upfront capital costs and achieve cost competitiveness with ICE vessels.

The fueling technology developed through the project provided the SFHC with safe and reliable refueling, resulting in zero safety incidents throughout the development and deployment of this technology. The mobile refueling truck received and transported high pressure gaseous hydrogen from public hydrogen stations to the SFHC's launch and storage sites throughout California. The FIB's design and operation enabled ZEI's non-hydrogen SME team members to fuel the boat throughout its demonstration while maintaining equipment and personnel safety. Without the event of any emergency scenarios, the EFT was never deployed in practice but its applicability to off-road equipment remains of interest to ZEI. The successful deployment of this technology removes barriers to entry of other off-road equipment looking to be repowered by gaseous hydrogen technology. This mobile hydrogen ecosystem can be brought to remote locations and stood up in a matter of minutes, creating an alternative to the high costs and long lead times of permanent fueling stations. Even in areas where permanent infrastructure is the long-term goal for hydrogen fueling, this ecosystem can provide a stopgap for deploying hydrogen equipment during the installation of permanent infrastructure.

Throughout the project, ZEI recognized challenges that impacted project development that should be considered for future off-road hydrogen deployments. High hydrogen costs and reliable availability remain barriers to fuel cell adoption, with the heavy-duty station at the Port of Oakland, launched in May 2024, proving essential for consistent high-pressure hydrogen supply. Expanding such stations is critical for early adopters and new use cases with reduction in fuel costs critical to enabling commercially viable TCO for operators. Another challenge is the limited access to hydrogen equipment specifications and procurement data, requiring greater market transparency and OEM support to streamline adoption. Additionally, electrifying harbor crafts presents technical hurdles, such as aligning electric motors with traditional sterndrives. ZEI tackled this through extensive research, highlighting the need for standardized solutions for different hull types and power ranges. Throughout the development and demonstration of the project, technology transfer efforts involved engagement with members of the public to showcase safe hydrogen solutions. Vessel operators who interacted with the technology were interested in the unique benefits of fuel cells in marine applications. Members of the Marine Law Enforcement Training Center had a distinct interest in the quiet operational capabilities of the SFHC, noting how it would increase situational awareness and improve active-duty communication. Many hydrogen stakeholders saw the value of the flexibility that the FIB offered for hydrogen fueling, recommending numerous applications where rapidly deployed infrastructure would reduce adoption barriers. ZEI welcomes future requests from public or private entities who wish to engage in meaningful hydrogen technology knowledge transfer activities from this project.

The technologies developed for this project support California's climate goals through the simplification of adoption pathways for hydrogen in difficult-to-electrify applications. All the technology solutions developed through this project will require additional refinement and productization to meet commercial needs but serve as proof points for the viability of their adoption in real-world applications.

GLOSSARY

Term	Definition
BOP	Balance of Plant
CHSS	Compressed Hydrogen Storage System
DC	Direct Current
DGE	Diesel Gallon Equivalent
DOE	Department Of Energy
ECU	Electronic Control Unit
EFT	Emergency Fuel Tank
FCEV	Fuel Cell Electric Vehicle
FIB	Fuel Interface Box
GHG	Green House Gas
ICE	Internal Combustion Engine
MLETC	Marine Law Enforcement Training Center
MRT	Mobile Refueling Truck
OEM	Original Equipment Manufacturer
SFHC	Small Fast Harbor Craft
SME	Subject Matter Expertise
TPRD	Temperature Pressure Relief Devise

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Project Deliverables

Project Deliverables:

- General Vessel Arrangements and Rendering
- Critical Project Review Report #1
- Power Package Design Report
- Refueling Systems Design Report
- Hydrogen Safety Plan
- Build and Assembly Report
- Commissioning and Testing Report
- Critical Project Review Report #2
- Sea Trials Report
- Vessel Demonstration Plan
- Vessel Demonstration Report
- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Initial Fact Sheet
- Final Project Fact Sheet
- Final Presentation Materials
- Technology/Knowledge Transfer Plan
- Technology/Knowledge Transfer Report

Project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Technology / Knowledge Transfer Content

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APPENDIX A:
Technology / Knowledge Transfer Content

Several operators emphasized the performance and handling of the FCV Vanguard, particularly its acceleration characteristics. One operator noted that despite the boat's higher water displacement, due to higher system weight, the increased torque from the electric drive system allowed for comparable acceleration to an ICE boat:

"Although the Vanguard displaces more, the acceleration is not noticeably reduced because of the increased torque at lower RPMs. This allows the heavier vessel to climb onto a plane in a comparable, if not slightly faster, time."

Another operator commented on how well the boat operates relative to its previous ICE configuration, adding that the ability to tune the motor idle speed enhances maneuverability:

"The tunability in the motor idling speed allows for slower in-gear speeds, making it easier to navigate around the harbor."

Similarly, another respondent observed that while the general interface of the boat remained familiar, the electric drive system allowed for smoother adjustments in speed:

"The electric drive allowed for more refined changes in speed while underway and provided a much quieter and calming experience."

Operators highlighted the maneuverability and docking improvements due to the fuel cell boat's electric drive system. One user described how the reduced idle speed and electronic monitoring of the prop speed improved precision:

"The idle speed of Vanguard's electric drive is less than half of a typical ICE. This makes shifting movements significantly smoother, which has two benefits: decreased wear on the drivetrain and greater ease when maneuvering."

Another respondent explained that electric motors provide instant torque, reducing lag during shifts and improving control during docking:

"When an ICE is put into gear, there is a noticeable lag in the power response due to the low torque available at idle speeds. Whereas, when an electric motor is put in gear, the full rated torque is briefly applied, maintaining the prop speed with a near-instantaneous recovery after the drivetrain load is applied."

A key improvement noted by multiple operators was the noise reduction and operator comfort compared to ICE boats. One respondent highlighted the comfort benefits:

"The drive system operates quietly, making the experience less fatiguing and more enjoyable for longer durations."

Another echoed this sentiment, emphasizing that the quieter operation created a more pleasant and less stressful environment for operators.

The safety and reliability of the FCV Vanguard were also frequently mentioned. One operator pointed out the enhanced reliability and safety of the system due to its dual power sources and battery backup:

"Most significantly, the experience of operating a fuel-cell-powered boat is greatly improved by the inherent redundancy that comes with two primary power sources and a built-in battery backup. This greatly reduces stress on the operator and significantly improves overall safety and reliability."

One notable difference between the FCV Vanguard and traditional ICE boats is the operational differences and pre-launch process. A respondent described how startup procedures are streamlined with the fuel cell system:

"In an inboard ICE, the operator must open the engine cover and/or run a blower for an extended period to ensure no combustible fumes remain in the enclosed engine bay since last operation. Alternatively, the FCV Vanguard can start up right when you get in the water."

The FCV Vanguard has demonstrated performance characteristics similar to ICE boats, with key advantages in acceleration, maneuverability, and noise reduction. Operators particularly appreciated the ability to make refined speed adjustments, the quiet operation, and the increased safety features.

Press Releases

In Q4 of 2021, ZEI worked with project partners to create and distribute a press release aimed at building excitement around the future development for the Small Fast Multi-Use Harbor Craft Project. In addition to distribution of the press release ZEI engaged with journalists to develop articles around the project.

By Q4 2024 ZEI had completed the build and begun the demonstration of the Small Fast Multi-Use Harbor Craft. During the build, the project team dedicated specific efforts toward developing the visual and narrative aspects of the boat. The project team renamed the boat to the "FCV Vanguard" to make it more approachable to a general audience as well as developed materials around the challenges overcome and innovative technologies developed therein which would help advance the adoption of future hydrogen fuel cell technology demonstrations.

Table A-1 lists many of the distributions and articles developed from this initial press.

Table A-1: Project Launch Press Release List

Outlet	Article
H2-View	*'First-of-its-kind' hydrogen harbor craft to be developed in California*
Yahoo! Finance	*Zero Emission Industries Awarded 2 million grant*
PR Newsire	*Zero Emission Industries Awarded 2 million CEC grant*
Marine Log	*ZEI New Hydrogen Powered Craft Project Gets 2 million California Grant*
SHIP technology	*Zero Emission Industries Harbour Craft*
Clean Tech Concepts	*ZEI 2m Award for Hydrogen Small Fast Harbor Boat*
Hydrogen Central	*Zero Emission Industries Awarded $2M Grant to Create a First-of-its-Kind Hydrogen Fuel Cell Boating Vessel*
UC Irvine	*Zero Emission Industries Awarded $2 Million CEC Grant To Create a First-Of-Its-Kind Hydrogen Fuel Cell Boating Vessel*
H2 View	*Scaling up and meeting demands*

New Chant	*SoCalGas Backs Testing of Hydrogen Fuel Cell Technology for Marine Vessels – NBC Los Angeles*
NBC Los Angeles	*SoCalGas to Provide Funding For Testing of Hydrogen Fuel Cell Technology for Marine Vessels*
AP	*SoCalGas & California Energy Commission to Provide Funding to Test Hydrogen Fuel Cell Technology for Marine Vessels*
Stock Titan	*SoCalGas & California Energy Commission to Provide Funding to Test Hydrogen Fuel Cell Technology for Marine Vessels*
PR Newswire	*SoCalGas & California Energy Commission to Provide Funding to Test Hydrogen Fuel Cell Technology for Marine Vessels*

Table A-2 lists many of the initial distributions and articles developed from the press release.

Table A-2: Project Demonstration Press Release List

Outlet	**Article**
PR Newswire	*Zero Emission Industries Announces High-Performance Fuel Cell Powertrain System in Repower of World-First Hydrogen Go-Fast Boat*
Yahoo Finance	*Zero Emission Industries Announces High-Performance Fuel Cell Powertrain System in Repower of World-First Hydrogen Go-Fast Boat*
Fuel Cell Works	*Zero Emission Industries Announces High-Performance Fuel Cell Powertrain System in Repower of World-First Hydrogen Go-Fast Boat*
H2 Tech	*Zero Emission Industries announces high-performance fuel cell powertrain system*
Decarbonfuse	*Zero Emission Industries Announces High-Performance Fuel Cell Powertrain System in Repower of World-First Hydrogen Go-Fast Boat*
Forbes	*Company Announces An Attempt To Bring Hydrogen Power To Boats*
Marine Log	*VIDEO: ZEI takes wraps off hydrogen-powered speed boat*
NA Clean Energy	*Zero Emission Industries Announces High-Performance Fuel Cell Powertrain System in Repower of World-First Hydrogen Go-Fast Boat*

Source: Zero Emission Industries

The Earthlings 2.0 Podcast:

https://podcasts.apple.com/us/podcast/52-zeroing-in-on-hydrogen-for-marine-transportation/id1600156804?i=1000651905640

Marine Log Op-Ed:

https://www.marinelog.com/views/op-eds/op-ed-hydrogen-fuel-cells-for-small-boats/

https://www.marinelog.com/views/op-eds/op-ed-achieving-net-zero-emissions/

The Inevitable Podcast:

https://www.youtube.com/watch?v=kjmUG-lo0k4&t=10s

Shift Podcast:

https://podcasts.apple.com/gb/podcast/zeis-john-motlow-on-solving-hydrogen-infrastructure/id1137686333?i=1000674602589

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix B: Additional Data Analysis Detail

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APPENDIX B: Additional Data Analysis Detail

Power System Analysis Calculations

Calculated values of note are provided in Equations (1) through (5):

- Equation (1) calculates hydrogen H2 mass flow rate based on fuel cell current.
- Equation (2) evaluates fuel cell stack efficiency. Since this system is a proton exchange membrane fuel cell (PEMFC), stack efficiency is expected to exceed 0.5.
- Equation (3) evaluates fuel cell system efficiency, which accounts for balance of plant components (e.g., coolant pumps, air blowers, and other components). System efficiency is expected to exceed 0.45.
- Equation (4) calculates the round trip efficiency (RTE) of the battery system used in the SFHC powertrain. Assuming that this system is a lithium-ion battery, RTE is expected to approach and exceed 0.9.
- Equation (5) calculates the efficiency of the electric motor, or how effectively the motor converts electrical energy into rotational energy.

Table B-1: Table of Equations for Calculated Values

$\dot{m}_{H_2} = \frac{I_{FC}}{2F} * MW_{H_2}$	(1)
$\eta_{Stack} = \frac{P}{HHV_{H_2}\ \dot{m}_{H_2}}$	(2)
$\eta_{System} = \frac{P_{net}}{HHV_{H_2}\ \dot{m}_{H_2}}$	(3)
$RTE = \frac{\int P_{Battery}\left(P_{Battery} \geq 0\right)}{\int P_{Battery}\left(P_{Battery} \leq 0\right)}$	(4)
$\eta_{Motor} = \frac{P_{Motor\ Calculated}}{P_{Motor\ Electricity}}$	(5)

Source: University of California Irvine

Where I is current, F is Farraday's constant, MW is molecular weight, η is efficiency, P is power, and RTE is round-trip efficiency.

System-wide calculations are provided below in Equations (6) through (9):

- Equation (6) calculates the overall efficiency of the SFHC powertrain by evaluating the shaft power versus chemical power input.
- Equation (7) and (8) aim to calculate the amount of electricity delivered to the electric motor through the battery versus the fuel cell. Ultimately, all power to the electric motor originates from the fuel cell. These equations evaluate the percentage of electricity going through storage versus being directly used.
- Equation (9) calculates the amount of hydrogen used during a single trip by integrating hydrogen mass flow from the starting time of a trip through the end of the trip.

Table B-2: Table of Calculations for System Wide Calculated Values

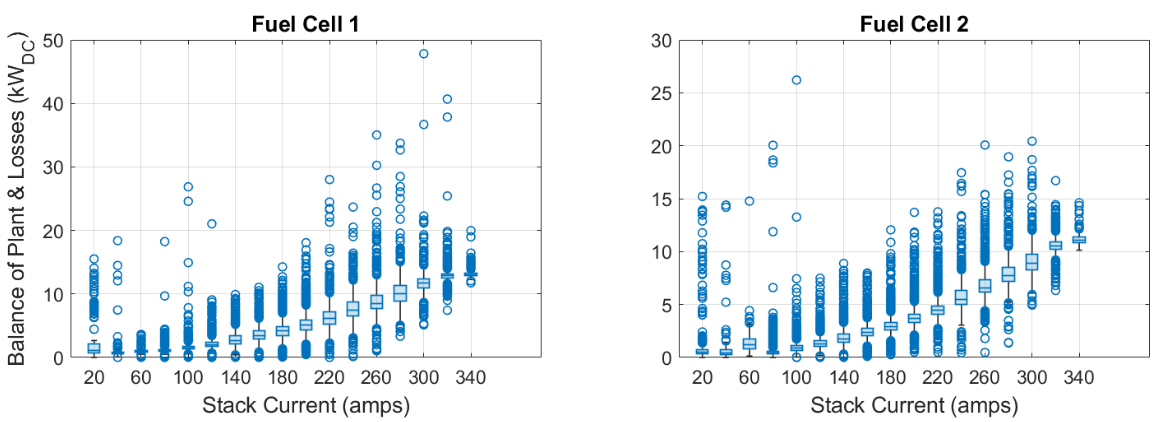
$\eta_{Powertrain} = \frac{P_{Motor\ Calculated}}{HHV_{H_2}\ \dot{m}_{H_2}}$	(6)
$Battery\ Fraction = \frac{\int_{\square}^{\square} \square\, P_{Battery}\left(P_{Battery} \leq 0\right)}{\int_{\square}^{\square} \square\, P_{Motor\ Electricity}}$	(7)
$Fuel\ Cell\ Fraction = 1 - \ Battery\ Fraction$	(8)
$m_{H_2} = \int_{t_{start\ of\ trip}}^{t_{end\ of\ trip}} \square\, \dot{m}_{H_2} dt$	(9)

Source: University of California Irvine

Additional Fuel Cell Battery and Motor Analysis

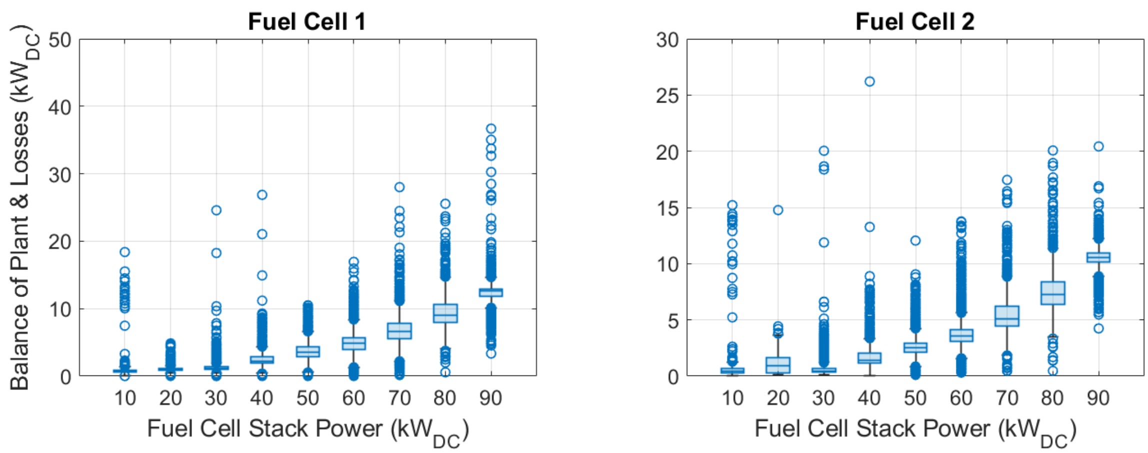
Fuel cell balance and DC/DC conversion losses versus stack current, stack power, and system power are shown in Figure B-1, Figure B-2, and Figure B-3 for stack current, stack power, and system power, respectively. However, there is insufficient data to separate fuel cell balance of plant (BoP) and DC/DC conversion losses. The increase in BoP loads and losses is likely due to the air compressor since these fuel cell stacks increase cathode airflow with stack ampacity. Since piping geometry remains constant, higher airflow requires increased velocity, leading to a cubic rise in compressor power demand. Although data is limited, coolant system power is expected to be minimal, as coolant pumps operate with significantly lower power requirements than air compressors. Additionally, DC/DC converters generally become more efficient as they approach the converter design ampacity.

Figure B-1: Fuel cell balance of plant loads and DC/DC conversion losses versus stack current



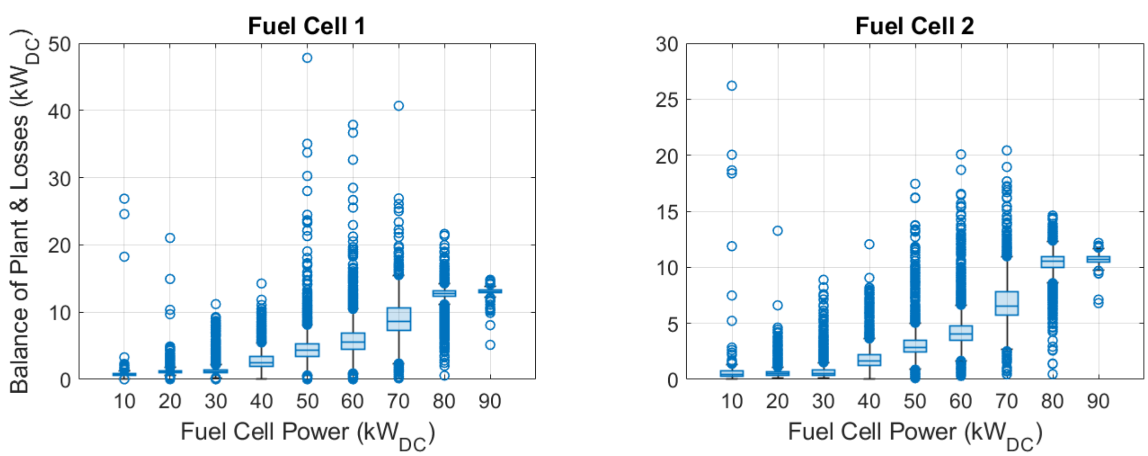
Source: UC Irvine, 2025

Figure B-2: Fuel cell balance of plant loads and DC/DC conversion losses versus stack power



Source: UC Irvine, 2025

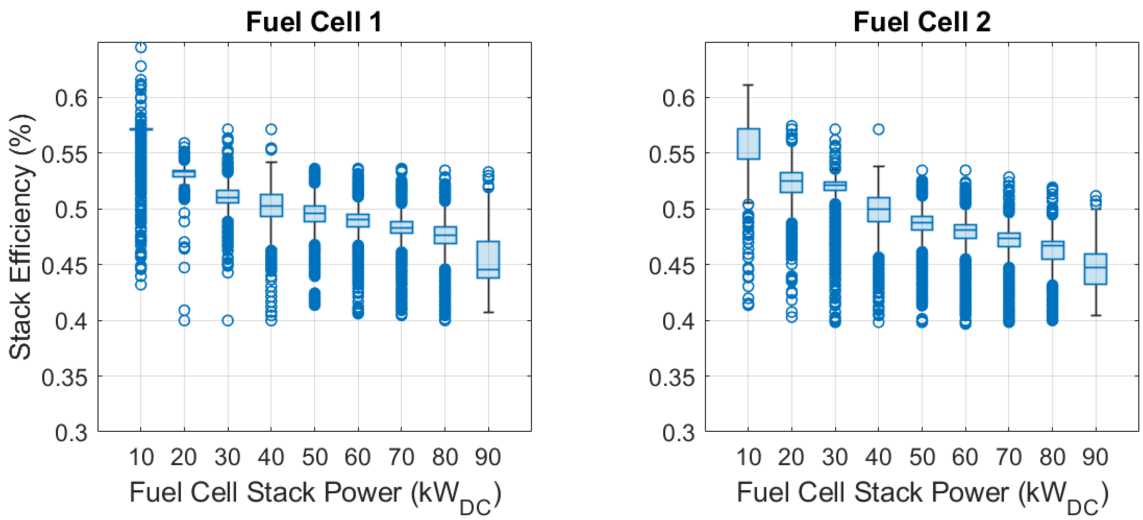
Figure B-3: Fuel cell balance of plant loads and DC/DC conversion losses versus system power



Source: UC Irvine, 2025

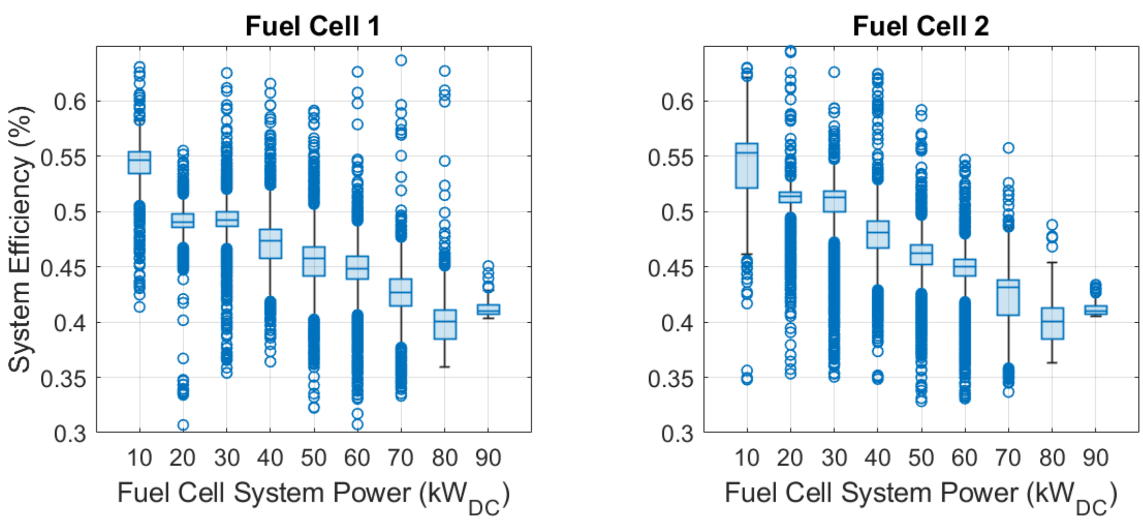
Fuel cell stack and system efficiency versus part load power is shown in Figure B-4 and Figure B-5, respectively. Part load data shows that the stack and system efficiency increase as power decreases, primarily due to higher stack voltage at lower loads (Figure 29).

Figure B-4: Fuel cell stack efficiency versus stack power



Source: UC Irvine, 2025

Figure B-5: Fuel cell system efficiency versus system power

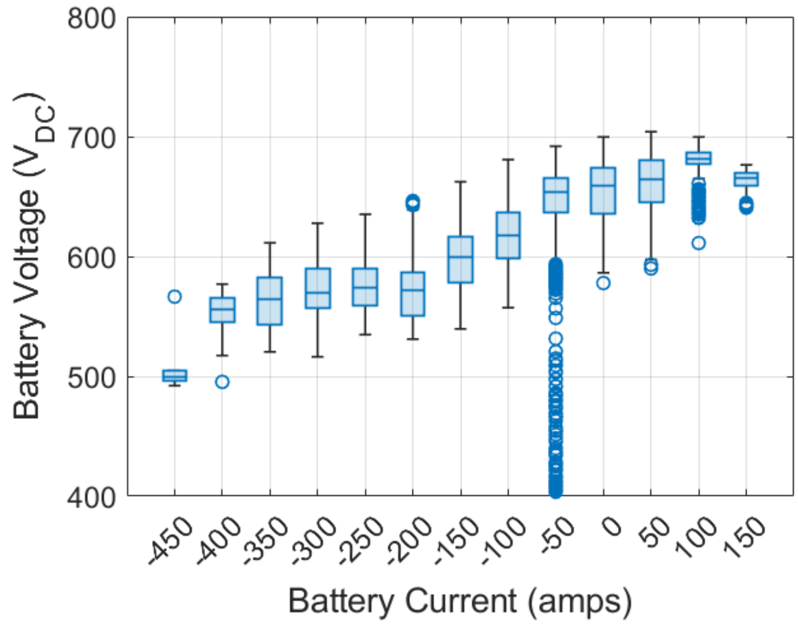


Source: UC Irvine, 2025

The voltage-current curve for the battery system is shown in Figure B-6. Within this chart, positive ampacity represents charging the battery from the fuel cells, and negative ampacity represents discharging the battery to power different loads on the vessel. The battery voltage-current curve shows quite different charging and discharging operation, where charging was limited to relatively low ampacities. In contrast, battery discharge resulted in large current pulls from the battery. In this particular instance, the data suggests a limiting current of 400 - 450 amps.

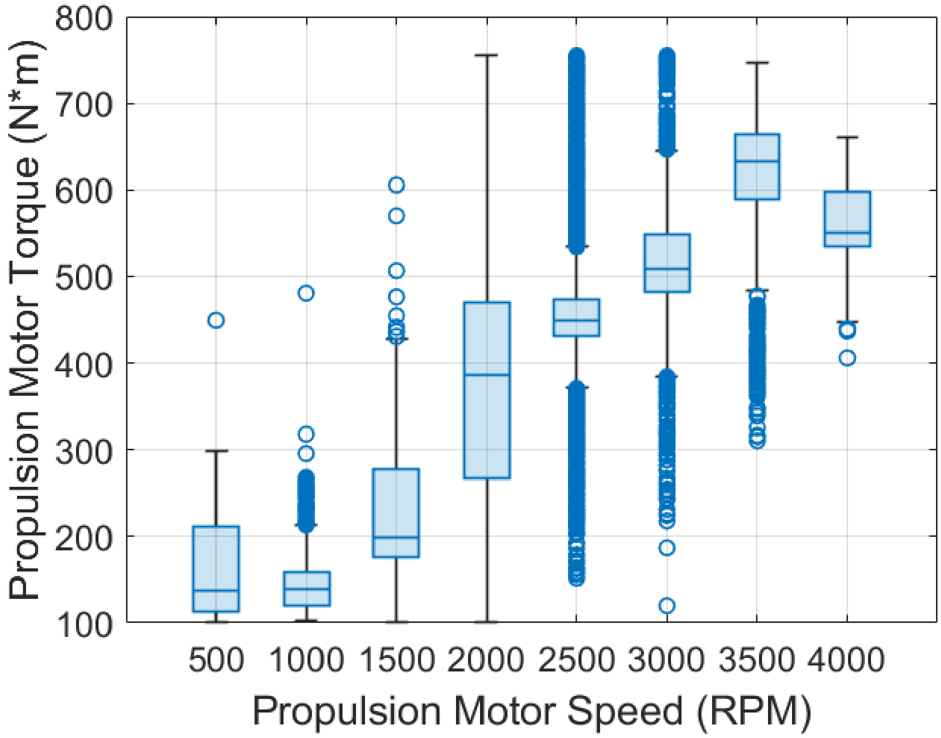
The final component examined in the powertrain component performance section is the propulsion motor. Propulsion motor torque versus motor speed is shown in Figure B-7 showing that motor torque increases with speed. A direct comparison of motor torque and speed verses vessel speed was not possible during measurement and verification due to mismatch between GPS and CAN data. Regardless, the data shows the propeller generates greater torque at higher motor speeds.

Figure B-6: Voltage-current results for the vessel battery system



Source: UC Irvine, 2025

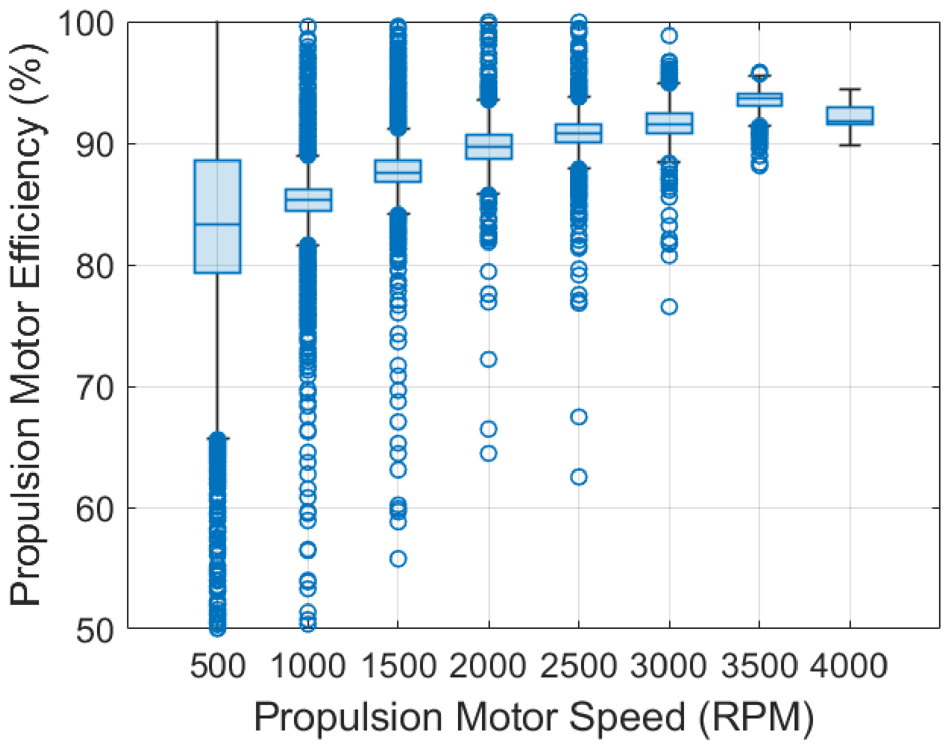
Figure B-7:Propulsion motor torque versus motor speed



Source: UC Irvine, 2025

Propulsion motor efficiency is defined as power output at the propeller (torque on the propeller shaft multiplied by the rotational speed of the motor shaft) divided by the DC electricity into the propulsion motor. This efficiency captures the DC/AC inverter losses, internal motor losses, and any other mechanical losses in the propulsion motor. Propulsion motor efficiency versus motor speed is shown in Figure B-8. Propulsion motor efficiency clearly increases with speed, regularly exceeding 90 percent once the motor is operating at 2000 revolutions per minute (RPM).

Figure B-8: Propulsion motor efficiency versus motor speed



Source: UC Irvine, 2025